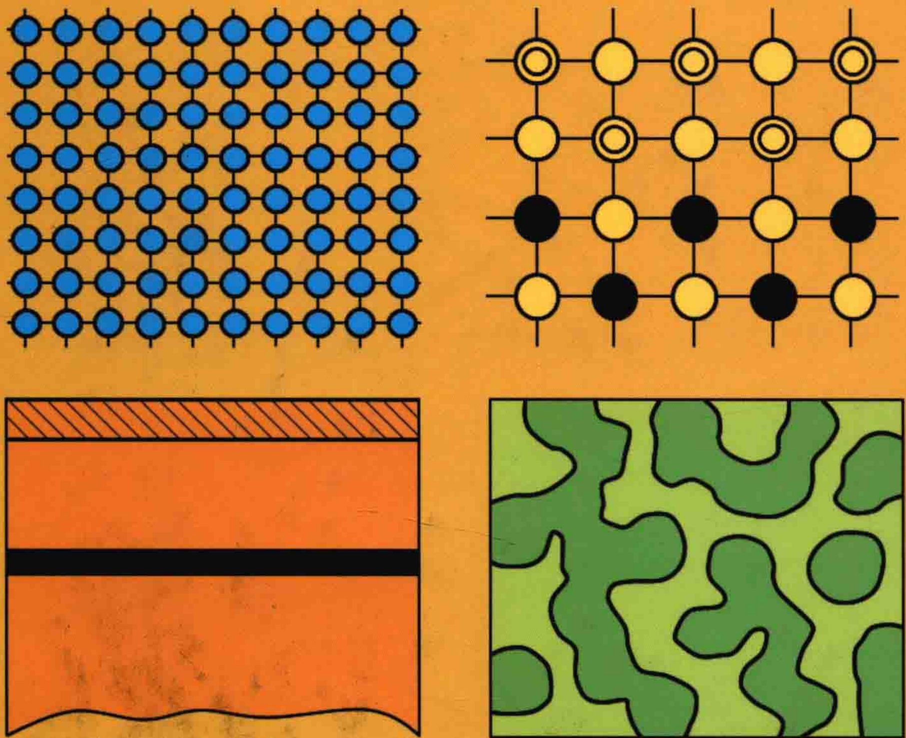
ENERGY FUTURES – Vol. 1

MATERIALS CONCEPTS FOR SOLAR CELLS



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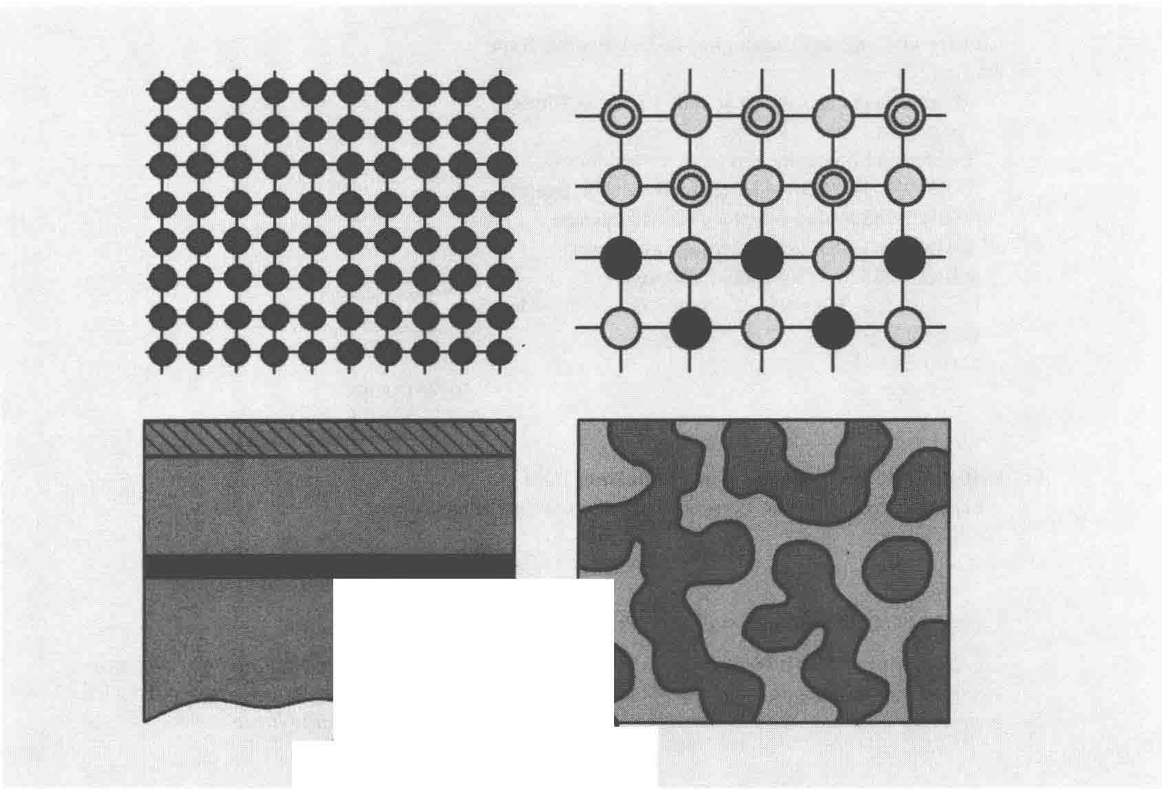

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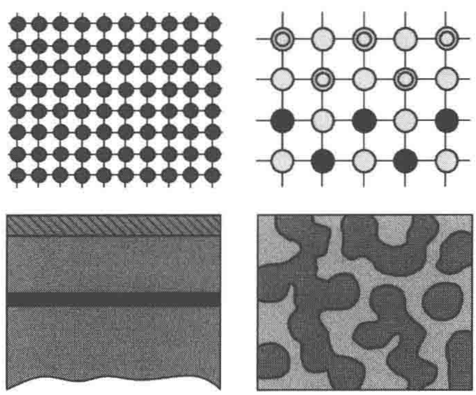

To my wife

Preface

This textbook results from lecture courses I have been giving to students who are interested in principles of solar energy conversion and in solar cell materials. Students listening to my courses usually study in the fields of engineering, materials science or natural science at universities around the world. I have had, and I continue to have, the great pleasure to teach not only in Europe but also in Asia, Africa and Latin America. A broad understanding of materials and combinations of materials for photovoltaic solar energy conversion helps to implement renewable energy worldwide. The textbook gives a comprehensive introduction to materials concepts for solar cells including basic principles and materials specific concepts.

The success in the development and application of solar cells is closely related to countless improvements of materials and to the development of new materials for solar cells. Quality criteria of solar cell materials are consequences of basic principles of solar cells. Materials and technological concepts follow from the ways in which different photovoltaic absorbers can be realized. Materials concepts of solar cells are based (i) on the growth of large crystals (wafer-based technology), (ii) on the growth of sophisticated layer systems on substrate crystals (epitaxy-based technology), (iii) on the deposition of absorber layers on foreign substrates (thin-film photovoltaics) and (iv) on the combination of very different materials on a nanometer scale (nano-composite solar cells). Interfaces between materials for charge separation, electric contacts to external leads and passivation are considered for all kinds of solar cells.

I would like to express my appreciation to all of my students, but especially those from the Free University Berlin for their interest and questions, to my former teacher Fred Koch for inspiration, to Günther

Seliger for the opportunity to teach at GPE (Global Production Engineering for Solar Technology) at the Technical University Berlin, to friends at the Kasetsart University in Bangkok and other universities around the world for supporting my teaching projects, to Martha Lux-Steiner at the Helmholtz Centre Berlin for giving me the opportunity to teach alongside my scientific work, to Bernhard Reinhold for discussing aspects of this textbook, to Brian Edlefsen Lasch for his critical reading of the manuscript, and to Catharina Weijman from Imperial College Press for excellent collaboration.

Thomas Dittrich
Berlin, 2013

Symbols and Abbrevations

Those Beginning with Latin Letters

A, A^-	acceptor, ionized acceptor
A	surface area
A	ampere, unit of the current
a	distance between two grid fingers
A/cm^2	unit of the current density
A_{cr}	area of a cross section
a_0	Bohr radius of the hydrogen atom (0.051 nm)
a_0	interatomic distance
A_{cell}	area of the solar cell
$a_{e1h1,b}$	radius of an exciton with the lowest energy in bulk semiconductor
a_{lc}	lattice constant
A_{fc}	area of the front contact
ALD	atomic layer deposition
AM	air mass
AM0	air mass zero
AM1.5d	air mass 1.5 for direct irradiation
AM1.5G	air mass 1.5 for global irradiation ($P_{sun}(AM1.5G) \equiv 1000\ W/cm^2$)
As	unit of the charge (ampere-second or Coulomb)
a-Si:H	hydrogenated amorphous silicon
a-SiC:H	hydrogenated amorphous silicon carbide
AU	astronomical unit

B	width
B	radiative recombination rate constant
B_{ideal}	radiative recombination rate constant of an ideal absorber
C	heat capacitance
C_A	Auger recombination rate constant
$C_{A,e}$	Auger recombination rate constant of electrons
$C_{A,h}$	Auger recombination rate constant of holes
c	velocity of light ($2.99 \cdot 10^8$ m/s)
C_{i0}	initial concentration of impurity atoms
C_{is}	concentration of impurity atoms in the growing crystal
C_m	concentration of impurity atoms in the melt
c-Si	crystalline silicon
CSS	close space sublimation
Cu_{In}^{2-}	copper replacing an In atom at a lattice side of a chalcopyrite
$CuInS_2$	copper indium disulfide
$Cu(In,Ga)Se_2$	copper indium gallium diselenide
CVD	chemical vapor deposition
D	diffusion coefficient
D, D^+	donor, ionized donor
d	thickness
d_{abs}	thickness of the absorber
D_e	density of states for free electrons in the conduction band
dE	interval of energy
d_{em}	thickness of the emitter layer
$d(h\nu)$	interval of photon energies
D_h	density of states for free holes in the valence band
D_i	diffusion constant of an impurity
d_k	thickness of kuvette
d_{local}	local thickness
D_n	diffusion coefficient of free electrons
D_p	diffusion coefficient of free holes
dbs	dangling bonds

$DOS_{st,a}$	density of donor-like surface states
$DOS_{st,d}$	density of acceptor-like surface states
dR	resistance of a very thin slice
D_{th}	thermal diffusion constant
dx	interval of distances
DSSC	dye-sensitized solar cell
E	energy (in units of eV)
e, e^-	free electron
E_A	energy of an acceptor
E_A	activation energy
E_{Ai}	activation energy of a diffusing impurity
$E_A^{SRH,pn}$	activation energy for Shockley–Read–Hall recombination in a pn-junction
E_{ab}	energy of an anti-bonding state
$E_{abs}(r_{QD})$	absorption edge of a semiconductor quantum dot
E_b	energy of a bonding state
E_C	energy of the conduction band edge, conduction band edge
$E_{C(n)}$	conduction band edge in an n-type doped region
$E_{C(p)}$	conduction band edge in a p-type doped region
$E_{C,abs}$	conduction band edge of the photovoltaic absorber
$E_{C,pass}$	conduction band edge of the passivation layer
E_{Cs}	conduction band edge at the surface of a photovoltaic absorber
E_D	energy of a donor
E_{e1h1}	lowest energy of an exciton
$E_{e1h1,b}$	lowest energy of an exciton in a bulk semiconductor
E_F	Fermi-energy
E_{F0}	Fermi-energy in thermal equilibrium
E_{Fm}	Fermi-energy of a metal
E_{Fn}	Fermi-energy of free electrons
$E_{Fn(n)}$	Fermi-energy of free electrons in an n-type doped region
$E_{Fn(p)}$	Fermi-energy of free electrons in a p-type doped region
$E^0_{F(n)}$	Fermi-energy in thermal equilibrium in an n-type doped region

E_{Fp}	Fermi-energy of free holes
$E_{Fp(n)}$	Fermi-energy of free holes in an n-type doped region
$E_{Fp(p)}$	Fermi-energy of free holes in a p-type doped region
$E^0_{F(p)}$	Fermi-energy in thermal equilibrium in a p-type doped region
E_{Fn}-E_{Fp}	Fermi-level splitting
E_{Fs}	Fermi-energy at the surface of a photovoltaic absorber
E_g	energy of the forbidden band gap
E_{g0}	energy of the forbidden band gap at the temperature of 0 K
E_{HL}	energy of the HOMO–LUMO gap of an organic semiconductor
$E_{HL}^{absorption}$	energy of the HOMO–LUMO gap for the absorption of an organic semiconductor
$E_{HL}^{transport}$	energy of the HOMO–LUMO gap for the transport in an organic semiconductor
E_{HOMO}	lowest energy of an unoccupied state in the HOMO band of an organic semiconductor
E_i	intrinsic Fermi-level
$E_{ion}^{D,A}$	ionization energies of donor and acceptor states
E_{ion}^{H}	ionization energy of the hydrogen atom (13.56 eV)
$E_{kin,e}$	kinetic energy of a free electron
$E_{kin,h}$	kinetic energy of a free hole
E_{LUMO}	lowest energy of an occupied state in the LUMO band of an organic semiconductor
E_{og}	energy of the optical band gap
E_{ph}	photon energy
E_{redox}	potential of a redox reaction
$E_{S/S+}$	energy of the ground state and of the ionized state of a dye molecule
E_S^*	energy of the excited state of a dye molecule
E_t	energy characterizing exponential absorption tails
E_t	energy of a trap state in the forbidden band gap
E_V	energy of the valence band edge, valence band edge

$E_{V(n)}$	valence band edge in an n-type doped region
$E_{V(p)}$	valence band edge in a p-type doped region
$E_{V,abs}$	valence band edge of the photovoltaic absorber
$E_{V,pass}$	valence band edge of the passivation layer
E_{Vs}	valence band edge at the surface of a photovoltaic absorber
E_{vac}	energy of the vacuum
eV	electron Volt, unit of energy
f	occupation probability of an electron
FF	fill factor
FTO	fluorine-doped tin oxide
FZ	float zone
G	generation rate of free charge carriers
G_0	thermal generation rate of an ideal absorber
G_e	emission rate of free electrons
G_{fn}	geometry factor for the diode saturation current density of electron diffusion
G_{fp}	geometry factor for the diode saturation current density of hole diffusion
G_h	emission rate of free holes
G_{sun}	photo-generation rate of an ideal absorber
GaAs	gallium arsenide
GaP	gallium phosphide
Ge	germanium
H	height
h	Planck constant ($6.626 \cdot 10^{-34}$ Js)
$\hbar$	Planck constant in terms of $h/(2\pi)$
h, h^+	free hole
H_n	thickness of the n-type doped region
H_p	thickness of the p-type doped region
HF	hydrofluoric acid
HIT	hetero-junction with intrinsic thin layer
HOMO	highest occupied molecular orbital

I	current, current density
I_0	diode saturation current, diode saturation current density
I_{00}	pre-factor of the diode saturation current density
$I_{0,SRH}$	diode saturation current density related to Shockley–Read–Hall recombination
I_D	current across a diode
I_{mp}	current, current density in the maximum power point
I_{ph}	photo current, photo current density
I_S	ionization energy of a semiconductor (in units of eV)
I_{SC}	short-circuit current (in units of A), short circuit current density (in units of A/cm^2)
I_{SC}	short-circuit current density in the diode equation
I^*_{SC}	short-circuit current density following from the I–V characteristics
I^{abs}_{SC}	short-circuit current density under consideration of transmission losses
I^{max}_{SC}	maximum short-circuit current density
I_{SRH}	diode current related to Shockley–Read–Hall recombination
$I_{tunn,e}$	tunneling current density for electrons
$I_{tunn,h}$	tunneling current density for holes
ILGAR®	ion layer gas reaction
In^{2+}_{Cu}	indium replacing a copper atom at a lattice side of a chalcopyrite
InP	indium phosphide
ITO	indium tin oxide
I–V	current–voltage (characteristics)
J_S	solar constant (1356 W/m^2)
k	wave vector
k	heat conductivity
k_0	segregation coefficient in equilibrium
k_B	Boltzmann constant ($1.38 \cdot 10^{-23}$ J/K)
k_e	momentum of a free electron
k_h	momentum of a free hole

k_s	segregation coefficient
KCN	potassium cyanide
kWh	kilowatt hour, unit of the electrical energy
L	length
L	diffusion length
L_{drift}	drift length
L_f	length of a grid finger
L_n	diffusion length of electrons
L_p	diffusion length of holes
L_{th}	thermal diffusion length
LPE	liquid phase epitaxy
LUMO	lowest unoccupied molecular orbital
m_e	electron mass in free space ($9.1 \cdot 10^{-31}$ kg)
m_e^*	effective mass of free electrons in the conduction band of a semiconductor
m_h^*	effective mass of free holes in the valence band of a semiconductor
MBE	molecular beam epitaxy
mc-Si	multi-crystalline silicon
MOCVD	metal organic chemical vapor deposition
MOVPE	metal organic vapor phase deposition
MOSFET	metal oxide semiconductor field-effect transistor
N	number
N	density of particles (units of cm^{-3})
N_C	effective density of states in the conduction band
N_{db}	density of dangling bonds
N_e	number of photo-generated electrons
N_{i0}	initial number of impurity atoms
N_{im}	number of impurity atoms
N_{ph}	number of incident photons
N_{st}	density of surface defects
$N_{st,a}$	density of acceptor-like surface defects
$N_{st,d}$	density of donor-like surface defects
N_t	density of defects in the forbidden band gap

N_V	effective density of states in the valence band
n	ideality factor in the diode equation
n	density of free electrons (unit in cm^{-3})
n_i	intrinsic density of free charge carriers
n^+ (n^{++})	density of free electrons in a highly (very highly) n-type doped semiconductor
n_0	density of free electrons in thermal equilibrium
n_n	density of free electrons in an n-type doped region
n_n^0	density of free electrons in an n-type doped region in thermal equilibrium
n_p	density of free electron in a p-type doped region
n_p^0	density of free electron in a p-type doped region in thermal equilibrium
n_s	density of free electrons at the surface of a photovoltaic absorber
n_t	density of occupied traps
n_{air}	refractive index of air
n_{AR}	refractive index of an antireflection coating layer
n_S	refractive index of a photovoltaic absorber
n_{TCO}	refractive index of a TCO layer
nwSC	nanowire solar cell
OVC	ordered vacancy compound
OSC	organic solar cell
P	electric power (in units of W)
P_e	sun's power received on earth
P_i	phosphorus atom at an interstitial lattice side
P_{inst}	installed power (in units of W_p)
P_{light}	light intensity (in units of W/cm^2)
P_{loss}	electric power losses due to resistive heating
P_{mp}	electric power in the maximum power point
P_{Si}	phosphorus atom at a lattice side in a silicon crystal
P_{Si}^+	ionized phosphorus atom at a lattice side in a silicon crystal
P_{sun}	areal density of the power of the sun received on earth (in units of W/m^2)