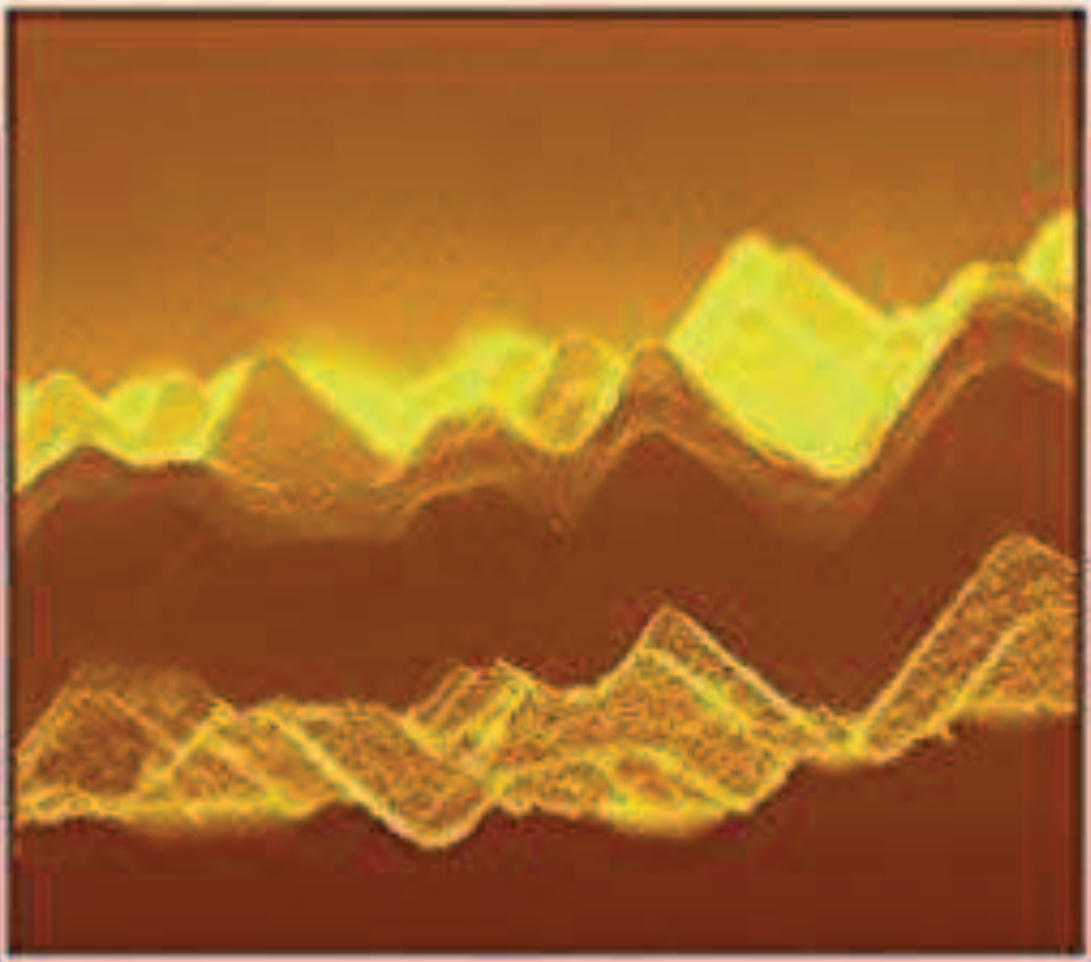
Rolf Brendel

Thin-Film Crystalline Silicon Solar Cells

Physics and Technology



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With a Foreword of A. Goetzberger

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O send Your light and Your truth,
let them lead me.

Psalm 43:3

Foreword

This book by Rolf Brendel closes a gap in the literature on photovoltaics, in particular on silicon solar cells. While there are several books on the general aspects of this topic available, they are limited mostly to the theory and practice of bulk silicon solar cells. The present book emphasizes thin silicon solar cells and treats the subject in a very comprehensive manner. Dr. Brendel is exceptionally qualified to write such a book because he has contributed personally in important ways to this field.

The crystalline silicon solar cell in its conventional form dominates today, with about 90% of the world market. This dominance of the market is on one hand surprising, because silicon as an indirect semiconductor has a relatively low absorption coefficient for a large fraction of the wavelengths of the solar spectrum. On the other hand silicon photovoltaics benefits from the large know-how developed in the past for all kinds of silicon devices. In order to absorb enough of the infrared sunlight to achieve a high efficiency, silicon cells have to have a thickness of several hundred micrometers. In addition, the material has to be of extreme purity and good crystalline perfection. Therefore the potential for cost reduction of this technology is limited. The impressive cost reduction achieved so far results partly from increased production volume and corresponding improvements of technology, but also from the availability of cheap surplus semiconductor-grade feedstock material. Photovoltaics profits from the fact that off-spec silicon not suitable for the semiconductor industry can still be used for solar cells. This dependence on the raw material base of another industry has its limitations, which are now being reached. Shortages of silicon for the photovoltaic industry are occurring periodically, depending on the ups and downs of demand in the semiconductor device market.

A completely different approach are thin-film materials with a direct bandgap. These genuine thin-film materials are characterized by a very high absorption. Therefore they are used with a thickness in the micrometer range. The oldest such material is amorphous silicon, which is mainly used for consumer products. Other strong contenders are chalcogenides like CIS (copper indium diselenide) and cadmium telluride. All these materials have been under development for many years and are now still in the stage of pilot production. It is still doubtful if they will reach the ambitious cost goals planned for them. The main reason for their slow progress seems to be the fact that both materials and technology have to be developed from scratch.

An alternative are thin layers of crystalline silicon on foreign substrates. As mentioned above, the problem of low absorptivity of this material has to be overcome. This can be done by clever optical design, as was pointed out many years ago. The key is multiple reflections of the light within the thin film. These concepts, however, remained theoretical until recently when the bulk silicon technology began to reach its limits. Several approaches exist for the realization of the crystalline thin-film solar cell. The most straightforward is the deposition of silicon from the gas phase by chemical vapor deposition. High-temperature and low-temperature approaches are possible. The best results have been achieved with the transfer technique, which uses films transferred from the surface of monocrystalline wafers. This technique, to wich the author of the present book has contributed extensively, requires a very small amount of silicon because the substrate can be used many times over.

The book starts with describing the present state of the technology of crystalline silicon cells. Then a very complete introduction to the theory of thin solar cells is given. The thermodynamic and quantum mechanical limitations of efficiency are outlined and then the practical limitations of efficiency are introduced step by step. Several new concepts are introduced. The experimental part starts with an exhaustive overview over the techniques for the realization of crystalline thin-film solar cells. The chapters on layer transfer processes are particulary interesting because the author describes many of his own results. Brendel has contributed a new concept, the PSI cell, wich combines the transfer technique with optimal light trapping by a waffle structure. The appendices contain more detailed theoretical treatments of some important subjects.

This book can be highly recommended for all interested in a new chapter of silicon solar cells which is just opening up.

A. Goetzberger
Fraunhofer Institute for Solar Energy Systems

Preface

Photovoltaics with thick crystalline Si wafers is a mature technology that is currently entering large-scale production. For a widespread solar electric power generation, however, a substantial reduction of the fabrication cost is required. For this purpose thin-film technologies are being developed with only micron-thick semiconductor layers for light absorption. While thin-film modules from amorphous Si, Cu(In,Ga)Se_2, and CdTe are already being commercially produced on a small scale, the development of thin-film modules from crystalline Si is still in the laboratory phase. This phase is characterized by competition of many different approaches for depositing and fabricating the thin crystalline Si solar cells.

This book is adressed to the physicist and the engineer who are interested in finding their way through the many approaches that are currently under investigation. It is also hoped that the reader gains an insight into the fundamental physical loss mechanisms that occur in solar cells. These physically inevitable losses set upper efficiency limits for thin-film cells that are more restrictive than for thick cells. The book also covers advanced device characterization by quantum efficiency analysis. If possible, analytic treatments of the optical and the transport properties are preferred. Such models permit a time-efficient and transparent modeling of many – obviously not all – the effects observed in thin-film cells. I encourage the reader to apply and modify these models to solve his own research problems. A review of recent developments in the field of thin-film crystalline Si cells discloses a wealth of novel technological routes towards highly efficient and potentially easy-to-fabricate thin-film crystalline Si modules. However, it is still by no means clear that any of these routes is clever enough to compete with conventional crystalline Si wafer technology, which is a fast-moving target for all thin-film technologies. If this book could inspire one of its readers to introduce new concepts for fabricating and understanding thin-film solar cells, it was really worth the effort of writing it.

The foundation of this book is my research conducted at the Max-Planck-Institut für Festkörperforschung (MPI-FKF) in Stuttgart from 1992 to 1997 and at the Bavarian Center for Applied Energy Research (ZAE Bayern) in Erlangen from 1997 to 2001. The other source of the book is a course on the "Physics of crystalline Si solar cells" that I held for graduate Physics students at the University of Erlangen-Nuremberg. The exchange of ideas with the students and colleagues contributed valuable aspects to my current understanding of solar cells and made the research on thin-film photovoltaics an exciting delight.

I thank Prof. H. J. Queisser, director at the MPI-FkF, for actively supporting my post-doc research and for his continuous encouragement to leave the beaten tracks. Much of my thin-film Si solar cell work had not been possible without successful cooperation with Prof. J. H. Werner during my time at MPI-FkF, sharing of visions with Dr. R. Plieninger, open-minded exchange of ideas with Dr. U. Rau, tedious lifetime measurements carried out by Dr. M. Schöfthaler, Dr. M. Wolf's quantum efficiency analysis work, and the excellent technical support of Dipl.-Ing. B. Fischer, Dipl.-Ing. B. Winter, and G. Markewitz.

I thank Prof. M. Schulz, director at ZAE Bayern, for giving me the chance to head the department for Thermosensorics and Photovoltaics and for the scientific freedom to establish new photovoltaic research activities at ZAE Bayern. I thank Dipl.-Ing. R. Auer for leading the technological work with an apparently never ending idealism, and Dr. V. Gazuz, Dipl.-Ing. W. Kinzel, and Dipl.-Ing R. Horbelt for fully committing themselves to solar cell fabrication. Many thanks also go to our PhD students Dipl.-Phys. M. Bail for lifetime measurements, Dipl.-Phys. K. Feldrapp for cell analysis, Dipl.-Phys. G. Kuchler for ion-assisted deposition, Dipl.-Phys. G. Müller for porous Si multi-layer design, and Dipl.-Phys. D. Scholten for multi-dimensional device simulations. The administrative skills of A. Kidzun greatly helped me to devote more of my time to science.

I also thank our project partners, Dr. S. Oelting from ANTEC GmbH in Kelkheim, Dr. H. Artmann and Dr. W. Frey from Robert Bosch GmbH in Gerlingen, Dr. H. v. Campe and Dr. W. Hoffmann from RWE Solar GmbH in Alzenau, Dipl.-Ing. J. Krinke and Prof. H. P. Strunk from the Institute of Microcharacterisation at the University of Erlangen-Nuremberg, Dipl. Phys. H. Nagel, M. Steinhof, and Prof. R. Hezel from the Institut für Solarenergieforschung Hameln (ISFH) in Hameln, and Dr. G. Wagner from the Institut für Kristallzüchtung in Berlin. I thank Dr. W. Appel from the Institut für Mikroelektronik Stuttgart for his willingness to perform high-temperature Si depositions on unusual substrates like glass and porous Si.

I thank my wife Christiane, who tolerated my absence from home on many evenings, weekends, and holidays throughout the last few years and actively supported my work on this book with her love.

Erlangen, March 2001 R. Brendel

Contents

APPENDICES

Symbols and Acronyms

Latin symbols

symbol	unit	
A		optical absorption
A_c	m^2	macroscopic cell area
A'		injection-dependent optical absorption
c	$m\ s^{-1}$	vacuum velocity of light
C		optical concentration factor
C_{max}		maximum optical concentration
C_n	$m^6\ s^{-1}$	Auger recombination coefficient for eeh processes
C_p	$m^6\ s^{-1}$	Auger recombination coefficient for ehh processes
D_{it}	$m^{-2} J^{-1}$	interface state density
D_n	$m^2\ s^{-1}$	electron diffusion coefficient
D_p	$m^2\ s^{-1}$	hole diffusion coefficient
E_C	J	edge of the conduction band
E_F	J	Fermi level at equlibrium
E_{Fn}	J	quasi-Fermi level of the electrons
E_{Fp}	J	quasi-Fermi level of the holes
E_g	J	semiconductor energy gap
EQE		external quantum efficiency
E_V	J	edge of the valance band
g	$m^{-3}\ s^{-1}$	carrier generation rate
G	A	photogeneration current
G	m	grain size
h	J s	Planck's constant
$\hbar$	J s	Planck's constant divided by 2π
$I_{AM1.5G}$	$W\ m^{-2}\ nm^{-1}$	energy flux density of global AM1.5 spectrum per wavelength interval
I_{mpp}	A	current at the maximum-power point
IQE		internal quantum efficiency
$IQE^{\bullet}$		corrected internal quantum efficiency under forward bias
j_E	$s^{-1}\ m^{-2}$	energy flux density per solid angle and energy interval
j_h	$A\ m^{-2}$	hole current density
j_n	$A\ m^{-2}$	electron current density
j_{sc}	$A\ m^{-2}$	short-circuit current density
$j_{sc}^{\bullet}$	$A\ m^{-2}$	maximum short-circuit current or photogeneration
k	$J\ K^{-1}$	Boltzmann's constant
l	m	path length of light in the cell
l		reduced minority carrier diffusion length L/G
$\bar{l}$	m	average path length of light in the cell
L	m	minority carrier diffusion length in the base of the cell

L_C	m	Collection length derived from quantum efficiency measurements under spatially homogeneous carrier generation
$L\{f\}$		Laplace transform of function f
L_J	m	diffusion length from the current-voltage curve $j(U)$
L_Q	m	diffusion length from *IQE* for strongly absorbed light
$L_{Q\infty}$	m	diffusion length from *IQE* for weakly absorbed light
L_α	m	optical absorption length
m		multiplicity: number of electron-hole pairs created per absorbed photon
n	m^{-3}	electron concentration
N_A	m^{-3}	acceptor concentration
N_D	m^{-3}	donor concentration
n_s		index of refraction of Si
n_{sur}	m^{-3}	surface or interface concentration of electrons
n_W	m^{-3}	electron concentration at the edge of the space charge region
N_γ	$m^{-2}\ s^{-1}$	photon flux density
$n_{\gamma c}$	$J^{-1}\ s^{-1}\ m^{-2}$	luminescence photon flux per photon energy interval and étendue
$n_{\gamma s}$	$J^{-1}\ s^{-1}\ m^{-2}$	photon flux of the sun per photon energy interval and étendue
p	m^{-3}	hole concentration
(p, q, r)		unit vector of the direction of propagation of a ray
P_{abs}	W	solar radiation power absorbed by the cell
P_{inc}	W	solar radiation power irradiating the cell
p_{sur}	m^{-3}	surface or interface concentration of holes
p_W	m^{-3}	hole concentration at the edge of the space charge region
q	C	elementary charge
Q_f	C	fixed charges in the dielectric layer
Q_G	C	charge on the metal gate or corona charges
Q_{it}	C	charge in interface states
Q_o	C	interface or surface charge at equilibrium
Q_{sc}	C	charge in semiconductor
$\mathbf{r}$	m	position vector
R		optical reflectance
R	$J\ s^{-1}\ m^{-2}$	radiance: power per area and projected solid angle
R_{Aug}	A	Auger recombination current
R_b		reflectance of the back reflector
R_{grb}	A	grain boundary recombination current
R_{rad}	A	radiative recombination current
R_s		surface reflectance
R_{SRH}	$m^{-3}\ s^{-1}$	Shockley-Read-Hall recombination rate
R_{sur}	A	surface recombination current
R_σ		ratio of electron to hole capture cross-section
S	$m\ s^{-1}$	surface recombination velocity
s_b		reduced back surface recombination velocity $S\ G/D_n$
S_b	$m\ s^{-1}$	back surface recombination velocity
S_{diff}	$m\ s^{-1}$	differential surface recombination velocity
S_{grb}	$m\ s^{-1}$	grain boundary recombination velocity

T		optical transmittance
T_c	K	temperature of the solar cell
T_d	K	deposition temperature
T_f		transmittance of the front surface of the cell
T_s	K	temperature of the sun
T_t		transmittance of front surface from inside the cell
U	V	voltage
U_{grb}	s^{-1} m^{-2}	grain boundary recombination rate
U_{mpp}	V	voltage at the maximum-power point
U_{oc}	V	open-circuit voltage
U_{rad}	s^{-1} m^{-3}	radiative recombination rate
U_{rec}	s^{-1} m^{-3}	recombination rate
U_{sur}	s^{-1} m^{-2}	surface recombination rate
U_t	V	thermal voltage
V_c	m^3	cell volume
W_{bas}	m	thickness of the cell's base
W_e	m	thickness of the cell's emitter
W_{eff}	m	effective film thickness: cell volume divided by macroscopic cell area
W_f	m	film thickness measured perpendicular to the collecting junction
W_{scr}	m	thickness of space charge region
W_{sub}	m	thickness of the cell's substrate
x		reduced x-coordinate X/G
X	m	x-coordinate
y		reduced y-coordinate Y/G
Y	m	y-coordinate
z		reduced z-coordinate Z/G
Z	m	z-coordinate

Greek symbols

symbol	unit	
α		Si facet angle relative to macroscopic cell surface
α_{eff}	m^{-1}	effective optical absorption coefficient
α_s	m^{-1}	optical absorption coefficient of Si
β		glass facet angle relative to macroscopic cell surface
γ		facet angle of the Si film relative to macroscopic cell surface
γ_E		photon of energy E
ε_o	F m^{-1}	dielectric constant of vacuum
ε_s	F m^{-1}	static relative dielectric constant of Si
$\mathcal{E}$	m^2	étendue: area times projected solid angle
η		efficiency: cell output power devided by incident radiation power
η_{abs}		efficiency: cell output power devided by absorbed radiation

		power
η_c		local carrier collection efficiency
η_{Car}		Carnot efficiency
η_{net}		efficiency: cell output power devided by net input radiation power
ϑ	rad	angle of light ray relative to cell normal
λ	m	wavelength of light
λ_g	m	wavelength of photons with bandgap energy E_g
Λ		Lambertian character of surface
μ_n	$m^2 V^{-1} s^{-1}$	electron mobility
μ_p	$m^2 V^{-1} s^{-1}$	hole mobility
τ	s	minority carrier lifetime in the base of the cell
Φ	$J C^{-1}$	electrical potential
Φ_o	J	neutrality energy level
Φ_λ	$m^{-2} s^{-1}$	flux of photons with wavelength λ
Ψ_{sur}	V	surface potential
ω	s^{-1}	frequency times 2 π
Ω	rad	solid angle

Latin acronyms

ac	alternating current
ABS	Alig-Bloom-Struck theoryfor impact yield
AM	air mass
AM1.5G	global solar spectrum of air mass 1.5
ARC	antireflection coating
a-Si	amorphous silicon
BSF	back surface field
CLEFT	cleavage of lateral epitaxial films for transfer
CPM	constant photocurrent technique for measurement of optical absorption index
c-Si	crystalline silicon
CV	capacitance voltage measurements
CVD	chemical vapor deposition
CZ	Czochralski
dc	direct curruent
EBIC	electron beam-induced current
ECR	electron cyclotron resonance
EQE	external quantum efficiency
GDMS	glow discharge mass spectroscopy
HF	high frequency
HTS	high-temperature substrate
IAD	ion-assisted deposition
IQE	internal quantum efficiency
ITO	indium tin oxide, a transparent conductor
LBIC	light beam-induced current
LCAO	linear combination of atomic orbitals

LPE	liquid-phase epitaxy
LTP	layer transfer process
LTS	low-temperature substrate
mc-Si	multi-crystalline Si
MNOS	metal oxide nitride semiconductor structure
MOS	metal oxide semiconductor structure
ONO	silicon oxide/silicon nitride/silicon oxide multi-layer stack
PCD	photoconductance decay
PC-plot	parameter confidence plot
PECVD	plasma-enhanced chemical vapor deposition
PERL	passivated emitter rear locally diffused
poly-Si	polycrystalline silicon
PSI	porous silicon
QMS	quasi-monocrystalline Si
QSSPC	quasi-steady-state photoconductance decay technique
rms	root mean square
SCR	space charge region
SEM	scanning electron microscope
SIMOX	separation by implantation of oxygen
SIMS	secondary ion mass spectroscopy
SiN_x	silicon nitride
SPC	solid-phase crystallization
SPS	sintered porous silicon
SRH	Shockley-Read-Hall recombination model
SRV	surface recombination velocity
SSP	silicon sheet from powder
STAR	surface texture with enhanced absorption and back reflector
TCA	$C_2H_3Cl_3$
TCO	transparent conducting oxide such as ZnO:Al or SnO_2:F
TEM	transmission electron microscopy
tpa	jump trials per surface atom
VEST	via hole etching for separation of thin films
VHF	very high frequency
VPE	vapor-phase epitaxy
XRD	X-ray diffraction
ZMR	zone melt recrystallization
1D	one-dimensional
2D	two-dimensional
3D	three-dimensional

Greek acronym

μc-Si	microcrystalline silicon with grain sizes < 1 μm