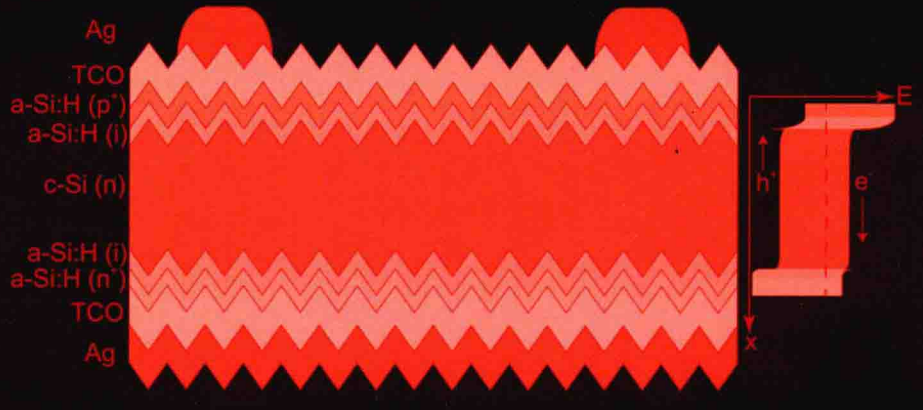
SEMICONDUCTORS AND SEMIMETALS

VOLUME 90

Advances in Photovoltaics
Part 3

Edited By

Gerhard P. Willeke and Eicke R. Weber



VOLUME NINETY

SEMICONDUCTORS AND SEMIMETALS

Advances in Photovoltaics: Part 3

Edited by

GERHARD P. WILLEKE
Fraunhofer Institute for Solar Energy Systems ISE, Freiburg, Germany

EICKE R. WEBER
Fraunhofer Institute for Solar Energy Systems ISE, Freiburg, Germany

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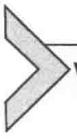

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SEMICONDUCTORS AND SEMIMETALS

Advances in Photovoltaics: Part 3

SERIES EDITORS

EICKE R. WEBER
Director
Fraunhofer-Institut
für Solare Energiesysteme ISE
Vorsitzender, Fraunhofer-Allianz Energie
Heidenhofstr. 2, 79110
Freiburg, Germany

CHENNUPATI JAGADISH
Australian Laureate Fellow
and Distinguished Professor
Department of Electronic
Materials Engineering
Research School of Physics
and Engineering
Australian National University
Canberra, ACT 0200
Australia

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PREFACE

The rapid transformation of our energy supply system to the efficient use of renewable energies remains to be one of the biggest challenges of mankind that increasingly offers exciting business opportunities as well. This truly global-scale project is well on its way. Harvesting solar energy by photovoltaics (PV) is considered to be a cornerstone technology for this transformation process.

This book presents the third volume in the series "Advances in Photovoltaics" in *Semiconductors and Semimetals*. This series has been designed to provide a thorough overview of the underlying physics, the important materials aspects, the prevailing and future solar cell design issues, production technologies, as well as energy system integration and characterization issues. In this volume, three distinctly different solar cell technologies are covered in detail, ranging from state-of-the-art crystalline silicon technology, the workhorse of the booming PV market, to one of the most advanced technologies, silicon heterojunction cells, and to an overview of thin film solar cell technologies. Therefore, this volume represents a cornerstone of "Advances in Photovoltaics," as the first and the third chapter together cover more than 98% of the current PV world market volume. The second chapter provides a glimpse into the future of highly efficient crystalline Si PV technologies that will allow further decrease in the cost of PV-generated electricity available from premium modules with top performance produced at prices that will become competitive with present-day low-cost PV modules. Following the tradition of this series, all chapters are written by world-leading experts in their respective field.

In the past 2 years, since the introduction to the first volume of this series has been written, the world PV market has undergone a decisive transformation. Huge production overcapacity, established especially in Asia, resulted in rapidly declining prices, often to values beyond the production costs, when fire sales of module supplies were the only way to generate desperately needed cash for financially stressed companies. Subsequently, many companies went into insolvency, followed by either restructuring under new ownership, often from abroad, or a complete shutdown of the production lines. The PV equipment manufacturers were especially hard hit, as they had to survive several years practically without any new orders.

Today we experience a new development: decreasing global production capacity begins to meet further increasing PV market size, the growth of which is fueled worldwide by the low cost of solar electricity. The consequence of this process will be the further decentralization of electricity supply, as PV systems increasingly allow owners of homes and industry to produce electricity on their own roofs and free areas, to the benefit of energy independence and the world climate, that desperately needs rapid further market penetration of renewables to decrease the emission of climate gases.

Gerhard P. Willeke and Eicke R. Weber
Fraunhofer ISE, Freiburg, Germany

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CHAPTER ONE

State-of-the-Art Industrial Crystalline Silicon Solar Cells

Giso Hahn[1], Sebastian Joos
Department of Physics, University of Konstanz, Konstanz, Germany
[1]Corresponding author: e-mail address: giso.hahn@uni-konstanz.de

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ABBREVIATIONS

A area
ALD atomic layer deposition
APCVD atmospheric pressure chemical vapor deposition
ARC antireflective coating
a-Si amorphous silicon
BSF back surface field
B_s substitutional boron concentration
$c_{A,n}$ ($c_{A,p}$) Auger recombination coefficient for electrons (holes)
c_{rad} radiative recombination coefficient
c-Si crystalline silicon
Cz Czochralski
d layer/wafer thickness d_{BSF}
D^+ diffusion constant in the BSF
DI deionized
D_n (D_p) diffusion constant of electrons (holes)
E energy
ECV electrochemical capacitance voltage
E_F (E_{Fi}) (intrinsic) Fermi energy level
EFG edge-defined film-fed growth
E_{Fn} (E_{Fp}) quasi-Fermi energy level of electrons (holes)
E_g band gap energy
E_{phot} photon energy
EQE external quantum efficiency
E_t energetic position of the trap level
EVA ethylene vinyl acetate
FCA free carrier absorption
FF fill factor
FZ float zone
h Planck's constant
HIT heterojunction with intrinsic thin-layer
I current
IBC interdigitated back contact
IPA isopropyl alcohol
IQE internal quantum efficiency
j current density
j_0 saturation current density
j_{01} (j_{02}) saturation current density of the first (second) diode
j_{0e} saturation current density of the emitter

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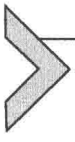
j_l light-generated current density
j_{sc} short circuit current density
k Boltzmann's constant
L^+ diffusion length in the BSF
LFC laser fired contacts
L_n (L_p) diffusion length of electrons (holes)
LPCVD low pressure chemical vapor deposition
mono-Si monocrystalline Si
mpp maximum power point
mc-Si multicrystalline Si
n electron concentration
n^+ (n^{++}) (very) highly n-doped
n_0 electron concentration in the dark
N_A (N_D) acceptor (donor) concentration
N_A^+ acceptor concentration in the BSF
n_{air} (n_{Si}, n_{SiN}) refractive index of air (c-Si, SiN)
n_i intrinsic carrier concentration
N_t trap density
N_{ts} areal trap density at the surface
O_i interstitial oxygen
p hole concentration
p^+ highly p-doped
p_0 hole concentration in the dark
PECVD plasma-enhanced chemical vapor deposition
PERC passivated emitter and rear cell
PERL passivated emitter and rear locally diffused
PERT passivated emitter and rear totally diffused
p_{phot} photon power density
PSG phosphor silicate glass
P_{surf} phosphorous surface concentration
P_{tot} total power loss
PV photovoltaic
q elementary charge
R recombination rate
R_A Auger recombination rate
R_{rad} radiative recombination rate
R_s series resistance
$R_{s,tot}$ total series resistance
R_{SRH} Shockley-Read-Hall recombination rate
R_{sh} shunt resistance
R_{sheet} sheet resistance of the emitter
s (s_n) (s_p) surface recombination velocity (of electrons or holes)
s_b surface recombination velocity at the backside
SCR space charge region
s_{eff} effective surface recombination
SIMS secondary ion mass spectrometry
SRH Shockley-Read-Hall
STC standard test conditions (1000 W/m^2, AM1.5g spectrum, 25 °C)
UMG upgraded metallurgical grade

V voltage
v_n (v_p) thermal velocity of electrons (holes)
V_{oc} open circuit voltage
Wp Watt peak (power of 1 W under STC)
α absorption coefficient
ΔE_F splitting of quasi-Fermi levels
Δn excess charge carrier density
η conversion efficiency
Φ photon flux
λ wavelength
ρ_{Si} density of Si
ρ resistivity
σ_n (σ_p) capture cross section for electrons (holes)
τ_A Auger lifetime
τ_b bulk lifetime
τ_{eff} effective lifetime
τ_{rad} radiative lifetime
τ_{SRH} Shockley, Read, Hall lifetime
τ minority charge carrier lifetime



1. INTRODUCTION

Solar cells fabricated based on crystalline Si (c-Si) generate electricity from sunlight by absorbing photons and generating electron–hole pairs, which are separated by a pn-junction. The pn-junction creates an electric field in the semiconductor and the separated charge carriers have to leave the solar cell via electrical contacts to perform work in an external circuit. A solar cell in operation is therefore essentially an illuminated large area diode, where emitter and base regions are contacted by metals to extract the carriers.

1.1. History

The first c-Si solar cell operating using the principle described above was reported in 1953 (Chapin et al., 1954), although research toward this achievement dates back to the 1940s (e.g., Ohl, 1941; Shockley, 1950). In the decades to follow, research was first directed toward application of the photovoltaic (PV) effect in space (powering satellites) or for terrestrial stand-alone systems. As for those applications the total cost of power generation was not the main issue, research was mainly driven by improving the conversion efficiency η, which is the ratio between output power from the PV device (generated from the solar cell or complete solar module) and

input power (impinging photon flux). The oil crisis in 1973 led to considerations to use PV also for terrestrial applications in larger scale as an alternative to fossil fuels. Since then a lot of R&D activities was focused on reducing the cost of PV electricity generation to make it attractive for market penetration.

In research, a lot of progress was made in improving efficiency by developing new cell designs and applying novel processing steps, leading to efficiencies as high as 25% using standard test conditions (STC: 1000 W/m^2 illumination, AM1.5g spectrum, 25 °C) in 1999 (Zhao et al., 1999), indicating the efficiency potential of c-Si. This efficiency was reached on extremely pure float zone (FZ) silicon and on small scale (4 cm^2) without the main part of the front side metallization grid being taken into account for the efficiency measurement (so-called designated area measurement) and using a very complex processing scheme. For most industrial applications, a full area measurement and cost-effective c-Si materials are of higher interest. In addition, the number and complexity of processing steps needed for cell fabrication has to be low, to allow a cost-efficient production. Here, the main challenge for industrial c-Si solar cells becomes visible: there is a trade-off between more complex processing on higher quality material allowing higher efficiencies, and less complex processing, e.g., in combination with a lower c-Si material quality.

1.2. General routes for cost reduction

The lower efficiency for lower cost materials and less complex processing might be advantageous cost-wise at cell level, but as there are also area related cost factors at module and system level (e.g., costs for module glass and installation), the question which route is more promising is not easy to answer. Therefore, a lot of different technologies have been developed over the past decades. This includes c-Si materials as well as solar cell fabrication processes.

The Si feedstock of highest quality stems from the so-called Siemens route using rods for Si production from the gas phase, which still accounts for the majority of produced Si wafers for industrial solar cells, with fluidized bed reactors as an alternative (Fabry and Hesse, 2012). So-called upgraded metallurgical grade (UMG) Si can be produced with significantly less energy needed per kg of fabricated Si, but a higher impurity concentration is the consequence, with relatively high amounts of, amongst others, B and P still present acting as doping elements in Si. This might cause problems as after crystallization the material will be partly compensated, and due to

different segregation coefficients of B and P their concentrations and therefore resistivity, influenced by the net doping, changes with ingot height (Ceccaroli and Pizzini, 2012; Heuer, 2013).

For c-Si materials, three different material classes have been important for PV in the past, as they have already been in industrial production in significant quantities. Monocrystalline Si (mono-Si) pulled using the Czochralski (Cz) method shows the lowest amount of extended crystal defects (like, e.g., grain boundaries, dislocations, precipitates), but normally contains a high amount of O, mainly in interstitial form (O_i) (Zulehner, 1983). Cast multicrystalline Si (mc-Si) can be produced in a more cost-effective way, but contains due to the crystallization method used a higher amount of extended crystal defects and impurities in interstitial or precipitated form, originating mainly from the crucible wall and the crucible coating (Buonassisi et al., 2006; Schubert et al., 2013). See Coletti et al. (2012) for an overview on the role of impurities in c-Si for solar cells. For both methods, the crystallized ingot has to be sliced in wafers for subsequent solar cell processing. To avoid kerf and other Si material losses that easily amount to >50%, ribbon-Si techniques have been developed, crystallizing the Si wafer directly from the Si melt (Hahn and Schönecker, 2004). Of the three technology groups, ribbon Si is the most cost-effective technique to produce wafers, but these wafers normally show the highest defect densities, reducing the electronic quality of the as-grown wafer.

Apart from Si wafer quality, solar cell process complexity is the other main parameter determining the efficiency and cost structure of the solar cell. In this contribution, focus is laid on industrial solar cell production, but for a more complete picture also PV module and system aspects should be considered. The heart of a solar module and every PV system is the solar cell. The cells are stringed in series so that the same amount of current flows through all cells in a string and the voltages of the cells add up. This makes proper sorting of cells a necessity to ensure that cells of similar performance end up in a string, as the cell with the lowest current at operation conditions determines the current flowing through the string. Therefore, for all cells not only the peak efficiency, but also a tight distribution of cell parameters is important to facilitate sorting and matching of the cells. This means that in industrial fabrication homogeneous Si wafer quality and stable processes with large process windows are desired to minimize the spread of quality in c-Si solar cell production.

In this chapter, an overview on industrial state-of-the-art c-Si solar cells is given. As there is not only one industrial solar cell process, but a variety of different processes applied for different cell designs, we will restrict the

overview on the most common cell architectures. Other cell designs already used in industrial scale such as the interdigitated back contact (IBC), commercialized by company SunPower Corp. (Cousins et al., 2010), or the heterojunction with intrinsic thin-layer (HIT) concept pioneered by Sanyo (now Panasonic) (Ballif et al., 2014) allow for the highest efficiencies in commercial c-Si solar cells on large area cells with lab cell record efficiencies up to 25% on large area cells (Smith et al., 2014; Taguchi et al., 2013) and even 25.6% with a combined IBC-HIT approach (Panasonic, 2014), but the processes differ significantly from mainstream technology. Therefore, these designs of very highly efficient c-Si solar cells will be treated in other chapters (e.g., Ballif et al., 2014).

1.3. PV market today

Figure 1.1 demonstrates the very dynamic growth of commercial PV over the past decades, spanning more than four decades from around 1 MWp[1] in the early 1970s to >30 GWp in 2011. Annual growth rates over the past 10 years have been in the order of 50%, mainly driven by market stimulation programs like, e.g., the renewable energy law with a guaranteed feed-in tariff in Germany. As the German feed-in tariffs have been adjusted recently and the German PV market was the strongest worldwide, the growth slowed down in 2012 and 2013. Strong growth in recent years allowed for a tremendous reduction in production cost due to scaling effects in mass production

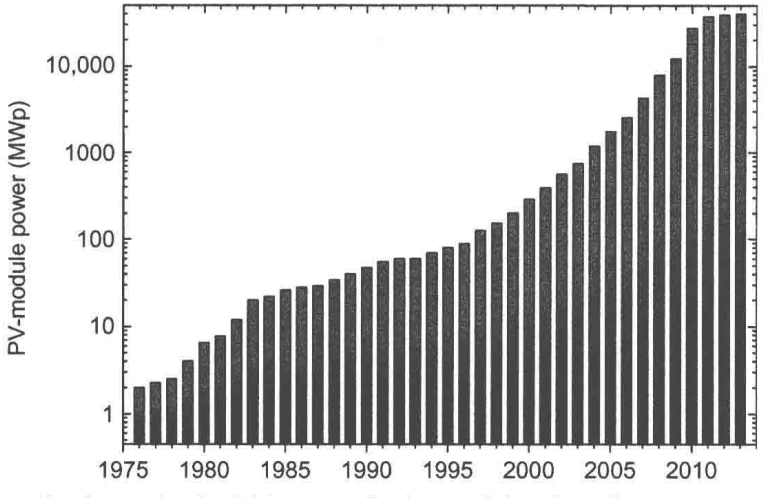


Figure 1.1 Yearly production/shipment of solar modules. *Data from PV News, Photon, and Mehta (2014).*

[1] Watt peak (Wp) refers to the power generated under STC.

as well as new and optimized processing technologies. This so-called learning curve effect of PV resulted in an average module price reduction of around 20% for every doubling of cumulated PV production (Nemet and Husmann, 2012). The continuing reduction in processing costs results in costs of a kWh generated by PV being now in the range of electricity generated from fossil fuels (depending on the installation site) (Kost et al., 2013).

The market share of different PV technologies shown in Fig. 1.2 reveals that c-Si still shows by far the highest market penetration, with thin film technologies like amorphous Si (a-Si), CdTe and $CuIn_xGa_{(1-x)}Se_2$ (CIGS) not really gaining market share above a 10–15% level. In contrast, latest figures indicate an even further increasing market share for c-Si of 90% in 2013, with roughly 67% based on mc-Si and 23% on mono-Si (Mehta, 2014). It is interesting to note that mono-Si lost market share to mc-Si in the past decade. This can be explained by the huge production expansion programs happening at most PV manufacturers in the past, as mc-Si technology seems to be easier to ramp up and was the more cost-effective way of production in the past. Whether this will hold true in the future, with new cell designs allowing for higher efficiency approaching the market, remains to be seen. The market share of ribbon-Si dropped to almost zero as the two main technologies edge-defined film-fed growth (EFG) and string ribbon are no longer on the market, due to the disappearing of their production companies Schott Solar and Evergreen Solar as well as EverQ, respectively.

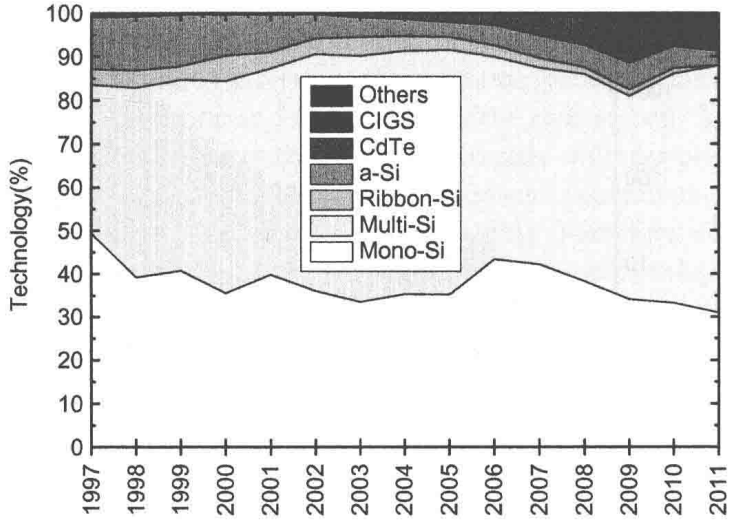


Figure 1.2 Market share of different PV technologies. *Data from PV News and Photon.*

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