MATERIALS PROCESSING THEORY AND PRACTICES
Volume 6
Series Editor F. F. Y. Wang

silicon processing for photovoltaics II

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SILICON PROCESSING FOR PHOTOVOLTAICS II

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VOLUME 6

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INTRODUCTION TO THE SERIES

Modern technological advances place demanding requirements for the designs and applications of materials. In many instances, the processing of materials becomes the critical step in the manufacturing processes. However, within the vast realm of technical literature, materials processing has not received its proper attention. It is primarily due to the lack of a proper communication forum. Since the materials processing is intimately concerned with specific products, those who are experts have no need to communicate. On the other hand, those who are involved with a different product will develop, in time, the technology of materials processing when required.

It is the objective of this series, Materials Processing – Theory and Practices, to promote the dissemination of technical information about the materials processing. It provides a broad prospective about the theory and practices concerning a particular process of material processing. A material process, intended for one technology, may have an applicability in another. This series provides a bridge between the materials engineering community and the processing engineering community. It is a proper forum of dialogues between the academic and the industrial communities.

Materials processing is a fast-moving field. Within the constraints of time and printed spaces, this series does not aim to be encyclopedic, and all-inclusive. Rather, it supplies an examination of material processes by the active workers. The view will be, by necessity, subjective. But the view will include both near-term and long-term prospectives. It is the fondest hope of this general editor that the volumes in this series can serve as first reference books in the field of materials processing.

Franklin F.Y. WANG
Stony Brook, New York.

PREVIOUS VOLUMES IN THE SERIES

1. Fine line lithography
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   C.P. Khattak and K.V. Ravi, volume editors
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7. III–V Semiconductor materials and devices
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PREFACE TO VOLUME 6

The processing of semiconductor silicon for manufacturing low-cost photovoltaic products has been a field of increasing activity over the past decade. A number of papers have been published in the technical literature. A previous volume (volume 5) in this series on Materials Processing–Theory and Practices presented comprehensive reviews on some of the key technologies developed for processing silicon for photovoltaic applications. This volume is complementary to the earlier volume and adds to the list of the important technologies.

The technological mix for production of photovoltaic modules has been changing and it is now possible to select out of a menu of technologies to suit the applications as an alternate to single-crystal silicon wafer processing. One of the areas of increasing importance is the use of multicrystalline silicon wafers. The understanding, production, as well as processing of silicon wafers with grain boundaries require variations from the conventional processes. Further, depending on the technology used, the material shows different characteristics. This volume presents comprehensive reviews of seven technologies for processing silicon for low-cost photovoltaic applications. All these reviews are confined to silicon and no papers on non-silicon semiconductors are included.

The volume starts with a review on the effect of introducing grain boundaries in silicon. This chapter by De Pauw, Mertens and Van Overstraeten examines this problem from a theoretical point of view, correlates the mathematical formulation with experimental evidence, evaluates the influence of grain boundaries and microdefects, and suggests methods to reduce their influence. The next two chapters describe two different processes in commercial production for multicrystalline silicon ingots. Helmreich discusses the Wacker ingot casting process, the largest producer of multicrystalline silicon. Khattak and Schmid describe the adaptation of the heat exchanger method (HEM) of directional solidification and its use as a purification process. The EFG process review by Kalejs discusses the ribbon process which is widely gaining commercial status.

In contrast to the semiconductor industry, the silicon meltstock costs constitute a large portion of the final photovoltaic product costs. D'Aiello, Robinson and Miller discuss the epitaxial solar cell approach in order to minimize the use of high-purity silicon. Dietl, in his chapter, presents a comprehensive review of metallurgical ways of producing silicon meltstocks for photovoltaic applications. Both these approaches are alternatives to reducing costs of silicon starting material.

The final chapter describes an innovative type of solar cell in which light is collected on both sides of the solar cell. This fitting conclusion suggests that even though a number of technologies have been utilized for photovoltaics there is still room for newer approaches.

The editors of this volume have had the unique privilege of working with leaders in the fascinating field of photovoltaics and would like to express their gratitude to the contributors for their thoroughness of discussions and high quality of their contributors.

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CHAPTER 1

EFFECTS OF GRAIN BOUNDARIES AND INTRAGRAIN DEFECTS IN SILICON FOR PHOTOVOLTAIC APPLICATIONS

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Silicon Processing for Photovoltaics II, edited by C.P. Khattak and K.V. Ravi

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List of symbols

C_{GB}	Grain boundary capacitance
C_d	Depletion layer capacitance
D	Minority carrier diffusion constant
d	Grain size
E_F	Fermi-level energy
E_{MAX}	Maximum electric field at a grain boundary
FF	Fill factor of a solar cell
G	Half the average interdefect distance
g	Generation rate
g_{AM1}	Average AM1 generation rate
I_{EBIC}	Electron beam induced current
I_{LBIC}	Light beam induced current
I_{S1}	Saturation current of the first exponential
I_{S2}	Saturation current of the second exponential
J_r	Recombination current density at the defect surface
J_{sat}	Saturation current in a semiconductor
J_{sc}	Short-circuit current density of a solar cell
k	Boltzmann constant
L	Minority carrier diffusion length in the crystal between the defects
L_{eff}	Effective minority carrier diffusion length in a defected crystal
L_{AM1}	Effective minority carrier diffusion length at AM1 illumination level
m	Ideality factor of the second exponential
$n(r)$	Minority carrier concentration
$n_0(r)$	Equilibrium minority carrier concentration
n_i	Intrinsic carrier concentration
N_A	Acceptor dopant concentration
N_{is}	Total midgap surface state density at the defect surface
N^A_{is}	Midgap surface state density for acceptor levels
N^D_{is}	Midgap surface state density for donor levels

Q	Integrated excess minority carrier concentration in the volume around the defect
Q_{defect}	Total charge in the defect
$s(n(r_d))$	Surface recombination velocity at the defect surface
$s_{eff}(n(W))$	Effective surface recombination velocity at $r = W$
T	Temperature
V_{oc}	Open-circuit voltage of a solar cell
v_{th}	Thermal velocity of the carriers
w	Effective width of a grain boundary
W	Depletion layer edge
$\alpha(\lambda)$	Light absorption coefficient at wavelenght λ
ε_{Si}	Relative dielectric permittivity of silicon
ε_0	Absolute dielectric permittivity of silicon
$\varphi_n(r)$	Electron quasi Fermi level at r
$\varphi_p(r)$	Hole quasi Fermi level at r
$\psi(r)$	Electrostatic potential at r
ψ_B	Barrier height at the defect surface
σ_C	Carrier capture cross-section for a coulombic attractive recombination center
σ_N	Carrier capture cross-section for a neutral recombination center
τ_B	Bulk minority carrier lifetime in a crystal with intragrain defects
τ_{eff}	Effective lifetime in a defected crystal

Introduction

During the last decade a number of potentially low-cost solidification techniques for silicon materials useful for photovoltaic applications has been developed. These materials are solidified from very pure silicon. The cost reduction lies in the solidification technique, which proceeds at a higher rate and with lower cost equipment and materials relative to single crystalline silicon. The grain size of this material is very large. In order to distinguish this silicon from single crystalline and polycrystalline materials, the material is called semicrystalline or plesio* single crystalline.

Thermal stresses occur during cooling because of the high solidification rate, which results in non-uniform temperatures, and the adhesion of the solidified silicon to the crucible walls or the supporting substrates, which have a thermal expansion coefficient different from silicon. Also, due to the high reactivity of molten silicon, contamination from the crucible wall material occurs. As a consequence, these materials contain crystal defects like grain boundaries, dislocations and precipitates. The influence of these defects on the solar cell characteristics is the subject of this work.

An overview of the different silicon materials for photovoltaic applications has been given by Dietl et al. (1981) and by Ciszek (1982). Only the three most important, and at the same time the only commercially available, materials will be considered here: Silso (from Wacker), HEM (from Crystal Systems) and UCP (from Semix). These three materials have been solidified in a graphite mold or crucible from very pure silicon.

1. Modeling of grain boundaries and microdefects in defected silicon

In low-cost silicon materials flaws are found that are not present in good quality Czochralski (CZ) or Floating Zone (FZ) single crystalline silicon. These flaws affect both the majority and the minority carrier current flow.

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* Plesio is a Greek word, which means 'nearly'.