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A. Goetzberger
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Photovoltaic Solar Energy Generation

 Springer

Goetzberger · Hoffmann



Photovoltaic Solar Energy Generation

This comprehensive description and discussion of photovoltaics is presented at a level that makes it accessible to the interested academic and professional with an historical overview. The book outlines the relevance of photovoltaics today and in the future. Then follows an introduction to the physical background of solar cells and the most important materials and technologies, with particular emphasis placed on future developments and prospects. The book goes beyond technology by also describing the path from the cell to the module to the system, proceeding to important applications, such as grid-connected and stand-alone systems. The composition and development of the markets and the role of PV in future energy systems are also considered. Finally, the discussion turns to the future structure of energy supplies, expected to comprise more distributed generation, and addresses synergies and competition from other carbon-free energy sources.

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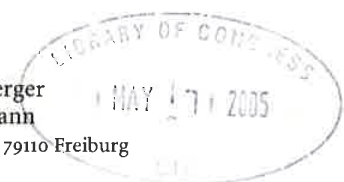
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Photovoltaic Solar Energy Generation

With 138 Figures

 Springer

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Preface

The intention of this book is to provide an impression of all aspects of photovoltaics (PV). It is not just about physics and technology or systems, but it looks beyond that at the entire environment in which PV is embedded. The first chapter is intended as an introduction to the subject. It can also be considered an executive summary. Chapters 2–4 describe very briefly the basic physics and technology of the solar cell. The silicon cell is the vehicle for this description because it is the best understood solar cell and also has the greatest practical importance. A reader who is not interested in the physical details of the solar cell can skip Chap. 2 and still understand the rest of the book. In general, it was the intention of the authors to keep the book at a level that does not require too much previous knowledge of photovoltaics. Chapter 5 is devoted to other materials and new concepts presently under development or consideration. It intends to provide an impression of the many possibilities that exist for the conversion of solar radiation into electricity by solid state devices. These new concepts will keep researchers occupied for decades to come. Chapter 6 gives an introduction to cell and module technology and also informs the reader about the environmental compatibility and recycling of modules.

The following chapters are devoted to practical applications. Chapters 7 and 8 introduce systems technology for different applications. The environmental impact of PV systems and their reliability is the subject of Chap. 9. It is pointed out that PV systems, in particular, modules belong to the most durable industrial products today. Systems efficiency is explained in Chap. 10. In particular, performance ratio, which permits comparison of systems independent of location, is introduced. In Chap. 11, we turn to questions of market and costs. Although PV is the most expensive renewable energy source today, it has a large cost reduction potential. Future cost can be predicted by referring to the learning curve that links cost to cumulated production. In order to realize this potential, PV needs long-term reliable public support. This support can occur in many different ways, as is shown in Chap. 11. The experience gained so far indicates that feed-in tariffs are the best market support mechanism.

Chapter 12 contains a vision of the future of PV. Decentralized systems in buildings, etc. have the best short- and medium-term prospects, but large-scale PV power plants are also a possibility for the more distant future. On

the other hand, PV is not the only renewable energy source, and in the future other such sources will be competing for markets. These other sources and how they compare to PV are discussed in Chap. 13. In Chap. 14, finally, frequently encountered arguments against PV are answered by referring to information provided in previous chapters of this book. In this manner, the summary and conclusion are combined in a somewhat unconventional way.

Freiburg, January 2005

Adolf Goetzberger, Volker Hoffmann

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1 What Is Photovoltaics?

1.1 What Is Photovoltaics?

Photovoltaics (abbreviated PV) is the most direct way to convert solar radiation into electricity and is based on the photovoltaic effect, which was first observed by Henri Becquerel [1] in 1839. It is quite generally defined as the emergence of an electric voltage between two electrodes attached to a solid or liquid system upon shining light onto this system. Practically all photovoltaic devices incorporate a pn junction in a semiconductor across which the photovoltage is developed (see Chap. 2). These devices are also known as solar cells. Light absorption occurs in a semiconductor material. The semiconductor material has to be able to absorb a large part of the solar spectrum. Dependent on the absorption properties of the material, the light is absorbed in a region more or less close to the surface. When light quanta are absorbed, electron hole pairs are generated, and if their recombination is prevented they can reach the junction where they are separated by an electric field. Even for a weakly absorbing semiconductor like silicon, most carriers are generated near the surface. This leads to the typical solar cell structure of Fig. 1.1.

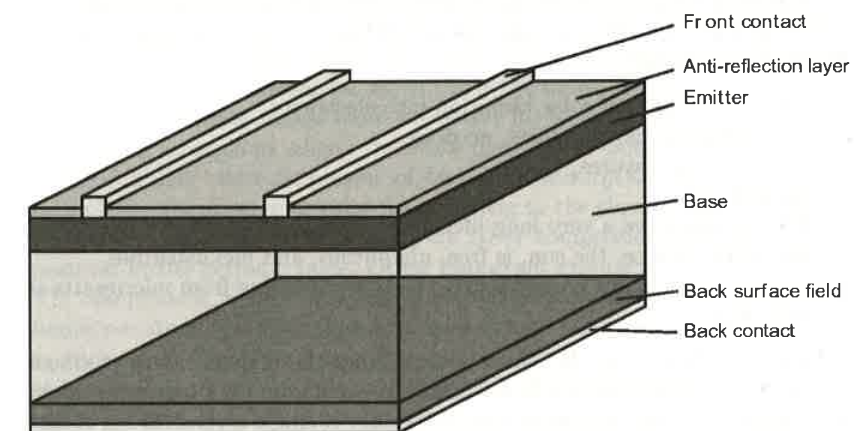


Fig. 1.1. Typical solar cell structure

3 Silicon Solar Cell Material and Technology

3.1 Silicon Material

Apart from oxygen, silicon is the most abundant element in the surface of the earth. It almost always occurs in oxidized form as silicon dioxide, as in quartz or sand. In the refining process, SiO_2 is heated to about 1800°C together with carbon. The metallurgic grade silicon that results from this process is used in large quantities in the iron and aluminum industries. Since it is only about 98% pure, it is not suitable as a semiconductor material and has to be further refined. This is done by transferring it into trichlorosilane (SiHCl_3), which is a volatile liquid. This liquid is distilled and subsequently reduced by reacting it with a hot surface of silicon, the Siemens process. Those two processes require a considerable input of energy and are the major contribution to the energy content of silicon solar cells.

3.2 Monocrystalline and Multicrystalline Silicon

3.2.1 Technology of Czochralski and Float Zone Silicon

In the beginning, only Czochralski (Cz) grown single crystals were used for solar cells. This material still plays an important role. Figure 3.1 shows the principle of this growth technique. Polycrystalline material in the form of fragments obtained from highly purified polysilicon is placed in a quartz crucible that itself is located in a graphite crucible and melted under inert gases by induction heating. A seed crystal is immersed and slowly withdrawn under rotation. At each dipping of the seed crystal into the melt, dislocations are generated in the seed crystal even if it was dislocation free before. To obtain a dislocation-free state, a slim crystal neck of about 3 mm in diameter must be grown with a growth velocity of several millimeters per minute. The dislocation free state is rather stable, and large crystal diameters can be grown despite the high cooling strains in large crystals.

Today, crystals with diameters of 30 cm and more are grown routinely for the semiconductor market. For solar cells smaller diameter crystals are grown because the usual solar cell dimensions are 10 cm by 10 cm or sometimes 15 cm

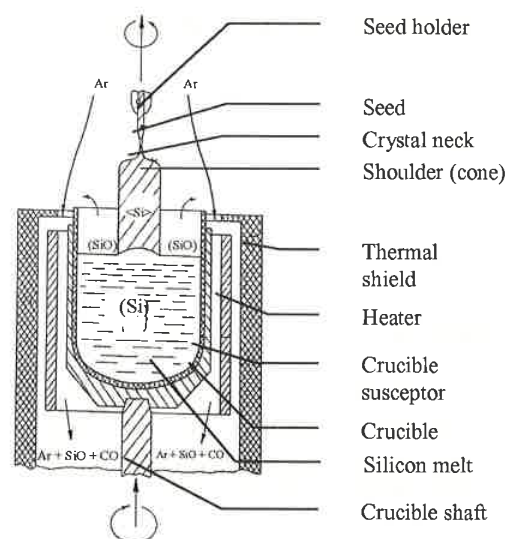


Fig. 3.1. Principle of the Czochralski growth technique

by 15 cm. The round crystals are usually shaped into squares with rounded corners in order to obtain a better usage of the module area.

The silicon melt reacts with every material to a large extent. Only silica can be used as a crucible material, because its product of reaction, silicon monoxide, evaporates easily from the melt. Nevertheless, Czochralski-grown crystals contain 10^{17} – 10^{18} cm $^{-3}$ of mainly interstitial oxygen. An alternative crystal growth technique is the float zone technique (Fig. 3.2). A rod of solid, highly purified but polycrystalline silicon is melted by induction heating and a single crystal is pulled from this molten zone. This material is of exceptional purity, because no crucible is needed, but it is more costly than Czochralski (Cz) material. In particular, it has a very low oxygen contamination which cannot be avoided with the Cz material because of the quartz crucible. Float zone (Fz) material is frequently used in R&D work. Record efficiency solar cells have been manufactured with float zone material, but it is too expensive for regular solar cell production, where cost is of overriding importance.

An interesting new development concerns tricrystals [14]. These are round crystals consisting of three single crystals arranged like pieces of a pie. They can be grown much faster and have higher mechanical stability. Solar cells of 0.1 mm thickness can be manufactured with a saving of 40% of the material.

For solar cells, as well as for all other devices, the crystal rods are separated into wafers of 0.2 mm to 0.5 mm thickness by sawing. This is a costly process because silicon is a very hard material that can only be cut with diamond-coated sawing blades. The standard process was the ID (inner diameter) saw, where diamond particles are imbedded around a hole in the saw

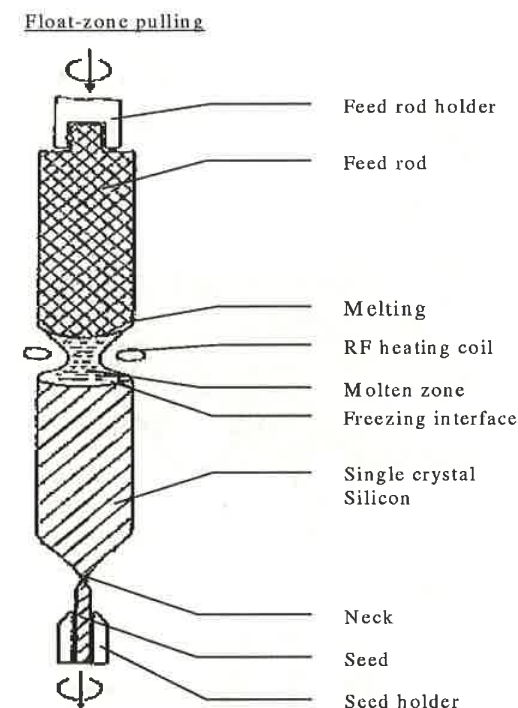


Fig. 3.2. Principle of the float zone technique

blade. A disadvantage of this process is that up to 50% of the material is lost in the sawing process. A new process was developed especially for solar cell wafers, the multi-wire saw (Fig. 3.3). A wire of several kilometers in length is moved across the crystal and wetted by an abrasive suspension whilst being wound from one coil to another. In this manner, thinner wafers can be produced and sawing losses are reduced by about 30%. It is interesting to note that wire saws are now also used for other silicon devices, an example of synergy in this field.

Another technology dating back to the 1970s is block casting [15], which avoids the costly pulling process. Silicon is melted and poured into a square graphite crucible (Fig. 3.4). Controlled cooling produces a polycrystalline silicon block with a large crystal grain structure. The grain size is some millimeters to centimeters and the silicon blocks are sawn into wafers by wire sawing, as previously mentioned. Cast silicon, also called polycrystalline silicon, is only used for solar cells and not for any other semiconductor devices. It is cheaper than single crystal material, but yields solar cells with a somewhat lower efficiency. An advantage is that the blocks easily can be manufactured into square solar cells in contrast to pulled crystals, which are round. It is