



Power Supplies for Crystal Growing

Introduction

The majority of voltaic cells are produced from crystalline silicon and because of increasing demand, driven by the need and incentives to produce more “green energy”. The best electrical efficiency that can be achieved using solar cells is about 20% and so at the moment converting solar energy is one of the most expensive ways of producing electricity and so a lot of effort has been spent on trying to increase efficiency without introducing additional costs in the production process. Furthermore, integrated circuits are built on single-crystal silicon substrates that possess a high level of chemical purity, crystalline perfection and structure uniformity.

A raw material such as quartzite, a type of sand, is refined into electronic grade polycrystalline silicon (EGS) using a complex multi-stage process and this is then used to grow single-crystal silicon by using either the traditional Czochralski or Float Zone Process. Large amounts of thermal energy are used in these processes and consequently the silicon wafer represents roughly 50% of the PV module cost.

There is also a growing demand for high-quality polysilicon feedstock in the world market in both the micro-electronic and photovoltaic industries. To fulfil this demand there is a requirement to:

- 1) increase the efficiency of crystal growth thereby reducing process costs and improving productivity, whilst maintaining quality,
- 2) reduce wastage caused by the sawing process and
- 3) produce thinner wafers.

This has led to the development of “crystal pulling” techniques which can produce silicon more efficiently and quickly but to the detriment of purity. Also because the silicon is produced as thin-walled tube or in film form the sawing operation has been replaced by less expensive cutting processes.

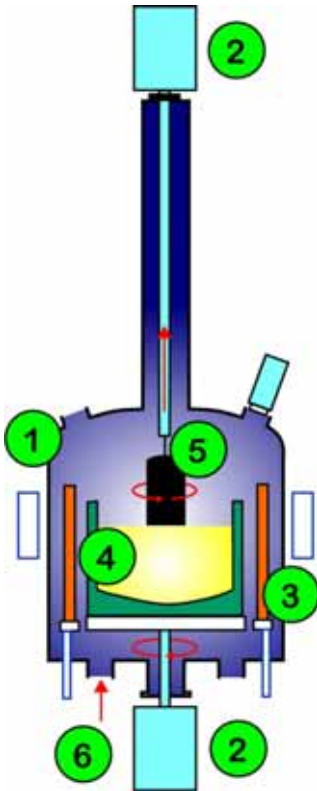
This quick guide explains the various techniques that are presently used for producing single-crystal silicon mainly used for the manufacturing photovoltaic modules used for producing electricity from solar energy.

REO ELEKTRONIK AG builds power supplies which help with efficient crystal growth by providing accurate control of the heating process.



A selection of products manufactured by REO ELEKTRONIK AG and REO INDUCTIVE COMPONENTS AG that are used for crystal growing.

Czochralski Crystal Growth (CZ)



This is the most common method of producing silicon monocrystals which are used for manufacturing semi-conductors and photovoltaic cells and involves placing raw polycrystalline material in a rotating crucible (4) in a vacuum chamber (1) and then purging with argon (6), whilst melting the silicon ($>1425^{\circ}\text{C}$) using a resistance heating system (3).

After the temperature of the silicon has stabilised a seed crystal is dipped into the molten liquid and rotated (5). The temperature of the crucible is then gradually lowered whilst the crystal is withdrawn from the melt, encouraging new material to grow onto itself.

CZ technology is mature and cost-effective but one of the drawbacks is that the ingots have a round cross-section whereas square PV cells are used because they are best suited for building into a solar panel. However, the waste material can be fed back into the growth process so it is not totally lost.



The cooled, single crystal silicon monocrystal ingot is shown in the diagram to the left.

A regulated, high-current power supply, required for heating the melt and maintaining accurate temperature control of a CZ process has been specially developed by REO ELEKTRONIK AG and this comprises a dual power system each with a three-phase thyristor controller, a water-cooled high-current transformer and a rectifier. It also has line reactors fitted to the mains input side of the system to reduce harmonic distortion. The unit provides two variable DC outputs (50kW and 150kW) which are controlled remotely from a Profibus network. The size of the power transformers and hence the whole system was considerably reduced by using water-cooling.

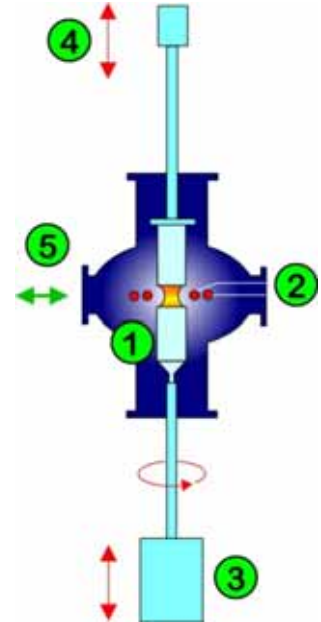


The picture shows the CZ power supply, REOTRON MDW Controller, water-cooled transformer and CNW line reactor

Float Zone Crystal Growth (FZ)

The float zone process involves passing a polysilicon rod through a heating zone. This produces ultra pure silicon and so provides a better quality ingot than the CZ process but is only used for approx. 20% of total silicon monocrystal production.

A polysilicon rod (1) is slowly moved, vertically (4) and rotated (3), in a chamber that is under vacuum or purged with an inert gas such as argon (5). This causes it to pass, from one end to another, through a heating zone about 1cm wide which is heated by an induction coil (2). Within the heating zone the ingot becomes molten which purifies the ingot, gradually, along its whole length.



Ribbon and foil growth techniques

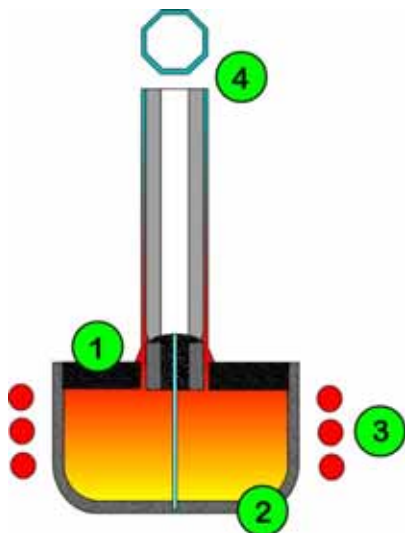
The cutting of solid silicon ingots into thin wafers wastes about 50% of the expensive, pure silicon feedstock and this has led to the development of several types of crystalline silicon foil. However, the quality of silicon produced by these methods does not approach that of the CZ and FZ processes.

Ribbon technologies may be grouped into two basic approaches “vertical” and “horizontal”. EFG, WEB and STR methods (with crystal growth and heat transfer parallel to the pulling direction) are examples of the vertical method, whilst RGS foil and the SF methods grow crystals in a horizontal-pulling configuration (with crystal angled towards to the pulling direction with perpendicular thermal conduction). Because of the difference in heat transfer the horizontal method allows high ribbon production rates.

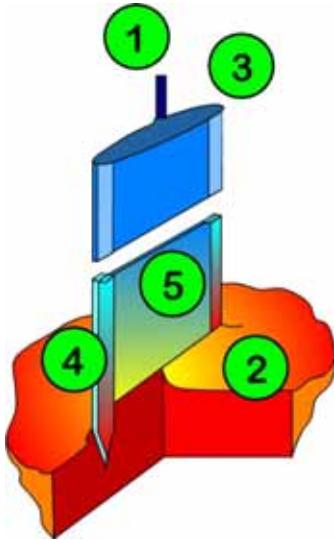
Edge Defined Film Fed Growth (EFG)

This is a very fast crystal growing method with no wafer sawing necessary. The silicon is formed in long (6m), octagonal tubes with sides that can be easily laser cut into the approximate the square shape of a solar cell which typically is 100 x 100mm.

The process was first tried in Tyco Laboratories in 1971 with subsequent funding by Mobil Solar Energy Corporation. Initially with single ribbons but later went on to octagonal crystal tube which has now been commercialised. Ownership was transferred to ASE Americas in 1994, which is when the transition to manufacturing was initiated. Nowadays this technique is used by RWE-Schott-Solar.



In this technique, the geometry of the ribbon is controlled by a slotted die (1) through which the silicon is fed via capillary action. A seed crystal is lowered until it contacts the molten liquid in the capillary, which forces the liquid level to rise above the die level but restrained by surface tension. As the seed is withdrawn the solidifying crystal draws more molten liquid into the die cavity, hence creating a continuous process. The die (1) and crucible (2) are integral components, i.e made from the same piece of graphite and induction heating (3) is used to melt the silicon. Growth is self-stabilising because the meniscus height increases with an increase in pull rate. The curvature of the meniscus causes the thickness of the crystal to decrease and this increases the rate of heat removal per unit area of the crystal growth interface, thus increasing the growth rate until it is again equal to the pull rate. The result is an octagonal tube of single crystal silicon.

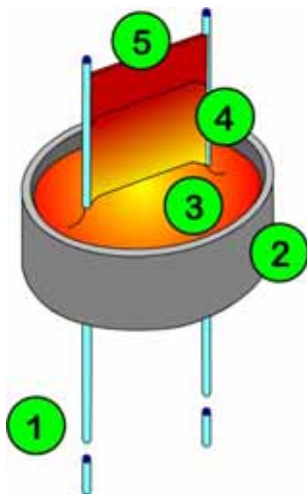


Dendritic Web (WEB)

Initiated with funding from Westinghouse in the 1970s and is now being used by EBARA Solar. The dendritic web crystal is grown directly from molten silicon in a crucible without the need for a shaping device. The dendritic seed 1) is lowered into a super-cooled melt and when it contacts the meniscus of the molten silicon 2) the growth starts to spread out laterally and form a button 3). As the seed is withdrawn, two secondary dendrites propagate from the extremities of the button 4), thus providing a frame to support a freezing ribbon 5). The dendrites grow into the melt that has been super-cooled by several degrees. Very accurate melt temperature control is required in order to maintain the super-cooled interface condition and to prevent “pull-out”.

String Ribbon (STR)

This process started with R & D in 1980s under the name of Edge-Stabilised Ribbon (ESR) and Edge-Supported Pulling (ESP) at the National Renewable Energy Laboratory and at Arthur D. Little respectively, before it was taken up in 1994 by Evergreen Solar.



The ribbon growth in this technique is achieved by “pulling strings” (1) that are fed through holes in the bottom of the crucible (2). The strings are pulled upwards, to raise the seed crystal (5) out of the molten silicon (3), to support the meniscus and ribbon (4), at a rate which sustains crystal growth. The thickness of the ribbon is controlled by surface tension, heat loss from the ribbon and pull rate. Unlike the WEB process there is no dependence on dendritic growth and so the temperature control is less critical.

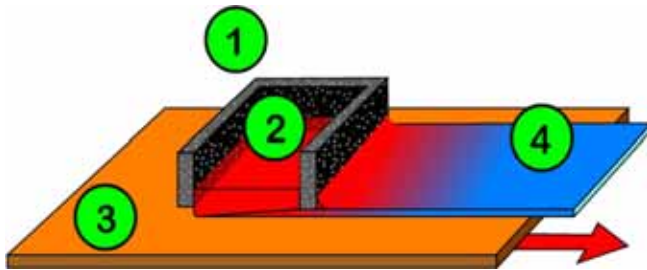
The picture on the right shows a typical control panel which was built by REO ELEKTRONIK AG for heating and controlling 12 crystal growing furnaces.

The main component used in this system was the REOTRON MEW DP thyristor controller, with a PROFIBUS interface which enabled each crystal growing station to be controlled and monitored remotely over a field bus network.



Ribbon Growth on Substrate (RGS)

First developed by Bayer but continued by the Energy Research Centre of the Netherlands and later by Deutsche Solar (a subsidiary of SolarWorld AG) and Sunergy Investco in the Netherlands (jointly known as RGS Development BV).



This is a horizontal-pulling technique, whereby a silicon melt reservoir (2) and die (1) are placed in close proximity to the top surface of a graphite/ceramic substrate (3), on which the ribbon/foil grows (4). In this method the area of growth interface can be very large compared to the foil thickness. It is possible to use substrates that can be recycled by removing the silicon foil when it has cooled.

Silicon Film (SF)

Details of the SF process are proprietary. The silicon crystal is grown in a thin layer directly upon either an insulating or conducting substrate, with a barrier layer that promotes nucleation. In the case on an insulating substrate, the barrier layer must act as a conductor to collect the current generated in the cell. In the case of a conducting substrate, the substrate can also act as an electrical conductor if *vias*, or holes, are used to connect the thin silicon crystal layer and the substrate. The SF thin film and barrier layer do not separate from the substrate on cooling as in RGS but become an active part of the solar cell.

Ribbon Technology Productivity Comparisons

The following table shows how many furnaces operating with an overall yield of 90% can produce 100 MegaWatts of electrical power generated from solar panels with 15% conversion efficiency.

Method/ parameter	Pull speed [cm/min]	Width [cm]	Throughput [cm/min]	Furnaces per 100 MW
WEB	1 - 2	5 - 8	5 - 16	2000
EFG Octagon	1.65	8 x 12.5	165	100
STR	1 - 2	5 - 8	5 - 16	1175
SF	no data available			
RGS	600 - 1000	12.5	7500 - 12,500	2 - 3

It can be seen that EFG Octagon is by far the most viable of the vertical pulling methods, whereas RGS is the best overall and probably has the best potential for the future. It should be noted that WEB and STR require simpler and low-cost furnace designs and so initial capital outlay is considerably less.

The main driver for justification of solar energy is the reduction of initial energy cost used for production of the solar panels, thus improving their *energy gain*. Even though solar energy may be the most expensive method of producing electricity from renewable sources, with a payback of between 1 and 20 years but usually under 5, it is still the most popular choice. Therefore by improving process methods this will make it even more viable and attractive. What is more, with global warming the amount of available solar power will increase.

Other methods

Other processes which are emerging include **Micro Spherical Silicon Technology** developed by Canadian Spherical Solar Power (a division of ATS), **Silver Cell Technology** by Origin Energy, Australia and **Crystal-line Silicon on Glass (CSG)**.

Multiple DC Power Supply

For accurate, co-ordinated control of power using a large number of load elements, such as in heating processes, it is possible to combine many switched-mode power supplies in one enclosure, as can be seen in the picture below.



The main component used in this system is the SMP-200-25 switch-mode power supply, designed and built by REO ELEKTRONIK AG. A field bus interface provided in each power supply is used for the remote adjustment of the voltage, current or power set-point and for enabling units as required. Internal parameters can also be set to match the application and continuously monitored by the supervisory system. Diagnostic displays are provided to assist with fault finding and to increase “up-time”.

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