Crystal Growth of Silicon for Solar Cells

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Weitere Fachgebiete > Technik > Werkstoffkunde, Mechanische Technologie > Materialwissenschaft: Elektronik, Optik

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Czochralski Silicon Crystal Growth for Photovoltaic Applications

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Abstract. The fast growing photovoltaic market is mainly based on crystalline silicon. The strong demand on silicon requires wafer manufacturers to produce high-quality material through high productivity processes with low-cost. Due to the higher energy conversion efficiency of single crystalline silicon (sc-Si), the Czochralski (Cz) pulling remains the key technology in photovoltaics. However, when compared with the multicrystalline silicon (mc-Si) production by the directional solidification, the current Cz technology is still more costly, due to the lower throughput and more energy consumption. Therefore, to retain the competition of sc-Si in the PV market, high efficient Cz ingot pulling is needed. In this chapter, we discuss some important issues in the Cz sc-Si production. Special focuses will be on the hot-zone design and multiple charges. The implementation of these concepts has led to significant cost reduction and yield improvement for both 6 in. and 8 in.-diameter solar-grade silicon in production. Some comments for the future development are also given.

2.1 Introduction

Photovoltaics (PV) is solar electric power that converts sunlight to electricity. Although the research and development of PV technology have been over 50 years, the solar market growth was slow until recent years due to the supports of various incentive programs, particularly in Japan and Europe. As a result, over the last 5 years, the markets have grown by an average of more than 35%. In 2007 alone, about 4 GWp PV modules were produced [1]. Among them, approximately 45% of the silicon was grown by the Czochralski (Cz) method, i.e., the same method for producing silicon for semiconductor industry. However, the module price drops in a rate of 20% per year, in which about 50% of the cost is attributed to the ingot and wafer production [2,3]. Therefore, how to reduce the production cost and increase the yield, without sacrificing much the quality, remains the key issue for crystal growers. Meanwhile, the low-cost and high-productivity of multicrystalline silicon (mc-Si) by casting has been increasing the market share, due to its higher throughput and lower energy

consumption. This also imposes a great challenge on Cz silicon producers to improve their process and lower the cost.

On one hand, the production per hour (PPH) is about $7\,kg\,h^{-1}$ for a current advanced GT 450 directional solidification (DS) furnace for a period of $50\,h$ in production (with a growth rate of $2\,mm\,h^{-1}$). On the other hand, for a Cz puller with $100\,kg$ charge and $30\,h$ growth time (with a pulling rate of $50\,mm\,h^{-1}$), the PPH is about $2\,kg\,h^{-1}$. On the other hand, the energy consumption for a DS furnace is about $10\,kWh\,kg^{-1}$, but for a Cz puller it is more than $30\,kWh\,kg^{-1}$. In terms of main power productivity, it could be 5–10 times more for the Cz growth depending on the level of automation. Therefore, to keep the Cz sc-Si growth competitive in the PV market, in addition to the significant improvement in the production efficiency, the high silicon quality is also crucial. Indeed, the improvement of 1% in solar conversion efficiency, which strongly relies on the crystal quality, could reduce the cell production cost about 7%, and the sc-Si production cost needs to be compensated by the cell production cost.

Efforts to improve Cz silicon growth usually focus on the hot-zone designs [4–11], multiple charges [12], crucible developments for lower cost and longer lifetime [13,14], and growth ambient control to reduce argon consumption and improve the yield [7,11]. At the same time, increasing charge, ingot diameter and length are also very useful to the throughput, in terms of PPH. Although using continuous casting is particularly effective on PPH, little effort has been paid until recently by SUMCO using the electromagnetic continuous casting (EMCC). In general, the PPH with the Cz process is typically about $1.5\,kg\,h^{-1}$, and for the mc-Si process, such as the heat exchanger method (HEM) [15] is about $3.5\,kg\,h^{-1}$ with energy and material costs being much lower [15,16]. The silicon charge up to $650\,kg$ has been reported recently, but the largest charge available for DS furnaces in the market for DS is about $450\,kg$. Therefore, to be competitive with the mc-Si process, significant process improvement, especially on high-speed pulling and multiple charges, for Cz growth is very important. The joint effort of Siemens Solar Industries (SSI) and Northwest Energy Efficiency Alliance (NEEA) is a successful story that the power reduction was more than 40% [7]. With multiple charges, a PPH up to $1.7\,kg\,h^{-1}$ was achieved [12]. In 2001, we also launched a similar project for high-efficient solar ingot growth, mainly for 5.5 in.-diameter solar ingots [11]. The project ended in 2003, and the improvement was better than that reported by SSI/NEEA. The reduction of power and argon consumptions was 65% and 53%, respectively. In addition, the pulling speed was increased 44%, and the yield with multiple charges was increased up to 31%. With the initial success, at the end of 2003, the effort was shifted to 8 in.-diameter solar ingots using the same type of furnaces. With an improved hot-zone, a PPH up to $2\,kg\,h^{-1}$ could be achieved for single charge. In this chapter, we briefly discuss the typical approaches toward the efficient solar ingot growth. Some comments for the future development are given as well.

2.2 Hot-Zone Design

Most of the hot-zone designs have been focused on the improvement in ingot quality for Cz silicon growth [4–7, 10]. However, for PV applications, the cost of ingot pulling is one of the major concerns, while the specifications for ingot quality are much flexible. Therefore, an efficient hot-zone for solar ingot growth is usually focused on the lower power consumption and the higher ingot pulling speed. With an effective hot-zone, the usage of the consumables, such as argon and graphite components (mainly the heater and susceptor), could also be significantly reduced. Computer simulation has been a useful tool for the hot-zone design, and several computer packages are available [17–19]. The calculated results are reliable if thermal properties are reasonably accurate [20]. We have been using STHAMAS [18] as a simulation tool for hot-zone designs, and the time for experimental trial-and-error has been significantly reduced. STHAMAS is a finite-volume based simulation package for axisymmetric growth systems developed by Muller's group in Germany. Melt and gas convections, as well as the face-to-face radiative heat transfer, are considered in this model. Figure 2.1 illustrates the approach for hot-zone design used in our research project. To ensure the reliability of the simulated result, benchmark comparison is very important. The inconsistency requires careful judgment, and sometimes tuning thermal data is inevitable because some simplifications are made in the simulation. This is particularly true for the bottom insulation. In reality, with four electrodes there, it is far away from axisymmetric.

For example, the hot-zone of a Kayex CG6000 puller, as shown in Fig. 2.2a has the crystal diameter of 5.5 in. and quartz crucible of 16 in.. The hot-zone could be divided into six major components: (1) radiation shield (or cone); (2) top side insulation; (3) additional side insulation; (4) bottom insulation; (5) top-wall insulation; and (6) argon venting. The default hot-zone from Kayex did not include the cone and the top-wall insulation. The room for the bottom and side-wall insulations was still large. The temperature distribution calculated by STHAMAS is also shown on the left hand side of Fig. 2.2a,
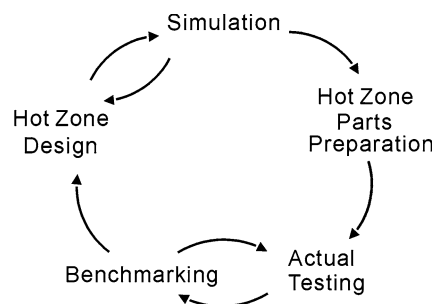

Fig. 2.1. A typical hot-zone design approach; the preparation of hot-zone parts could take several months
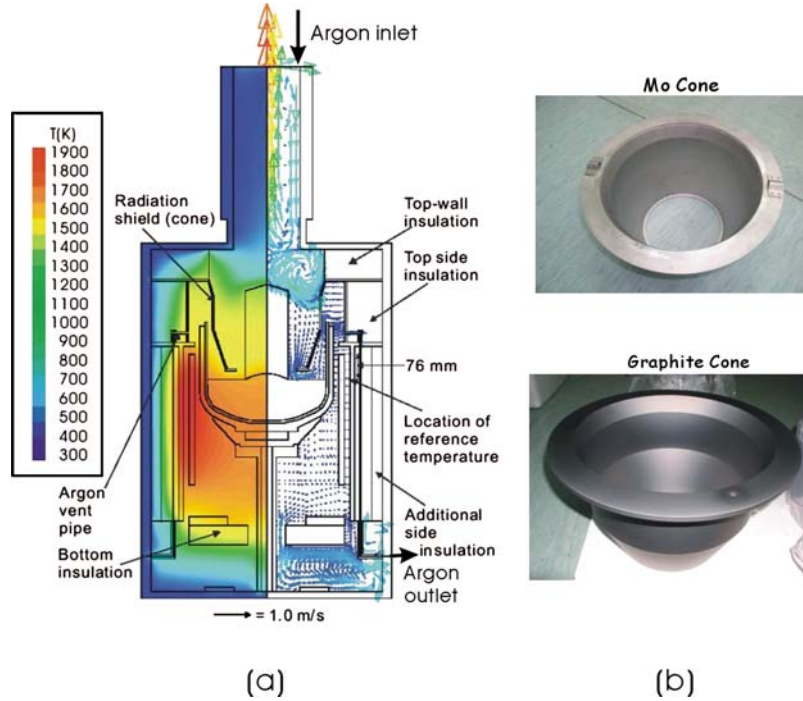
Fig. 2.2. (**a**) Schematic representation of the hot-zone (six major components) for a Kayex CG6000 puller using 16 in. crucible; typical thermal (*left*) and argon flow fields (*right*) are shown; (**b**) photographs for the molybdenum (*top*) and the graphite (*bottom*) cones

while on the right hand side, the argon flow field is shown. Both molybdenum (Mo) and graphite with coating have been considered for the cone material. Figure 2.2b shows the photographs of both cones. The lifetime of both cones is long, but the Mo cone is more robust and can be cleaned easily by sand blast.

2.2.1 Power and Growth Speed

The main purpose of using the cone is to block the thermal radiation from the melt to crystal, so that the crystal can be cooler and pulled faster. Such an idea can be easily understood from the energy balance at the growth interface:

$$k_S G_S - k_L G_L = \rho_S \Delta H V, \qquad (2.1)$$

where k_S and k_L are the thermal conductivities of the crystal and melt, while G_S and G_L are the thermal gradients in the solid and melt, respectively; ρ_S is the density, ΔH heat of fusion, and V the pulling speed. Obviously, as the thermal gradient G_S in the crystal is increased, the growth rate V can also
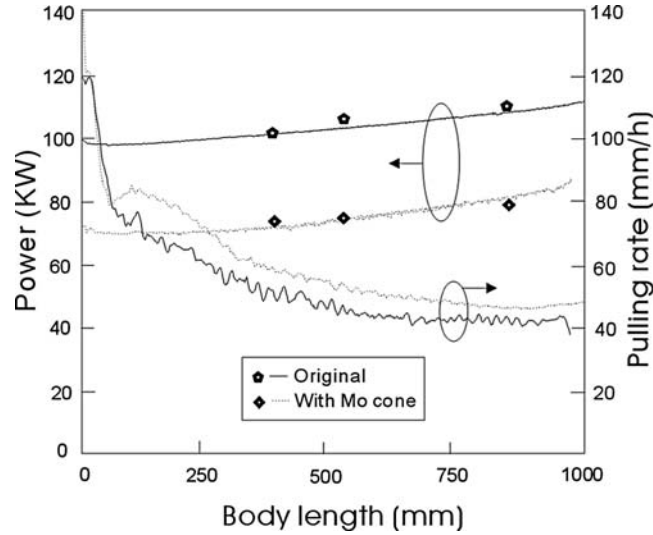
Fig. 2.3. History of power consumption and growth speed with and without molybdenum cone; the simulated data in power consumptions are included (*diamond symbols*) for comparison

be increased. The cone is used not only to block the thermal radiation, but also to reflect the radiation back to the melt. Hence, the cone material needs to have a high-reflectivity and can be operated at high-temperature, such as molybdenum. Graphite is also often used because of the low-cost. To enhance the reflectivity of the graphite cone, SiC or Pyrolitic Carbon (PC) coating can be used. Figure 2.3 shows the comparison of the power and pulling speed for the growth of 5.5 in.-diameter silicon without and with the Mo cone; other insulation options were not installed in this case. As shown, with the Mo cone, the power consumption was greatly reduced (from about 105 to 75 kW) and the growth speed was significantly increased. The average growth rate in the body (more than $50\,\mathrm{mm\,h^{-1}}$) was increased as well; the growth rate at the body length of 200 mm was up to $76\,\mathrm{mm\,h^{-1}}$ and the crystal quality and RRV (radial resistance variation) were still better than the original one. The better RRV for the wafer was due to the smaller interface concavity. The power consumptions predicted by STHAMAS were quite satisfactory for both cases. In addition to being as a radiation shield, the cone can be designed as a thermal insulator as well. In such a case, a composite cone is preferred.

To further reduce the power consumption, effective insulation is necessary. Through a few tests, we have found that the bottom insulation plays a critical role. With good bottom insulation, the power consumption could be further reduced to about 50 kW during the body growth. Figure 2.4 shows the improvements of several hot-zone designs on the power consumptions and growth speeds. The standard design (STD) refers to the original hot-zones,
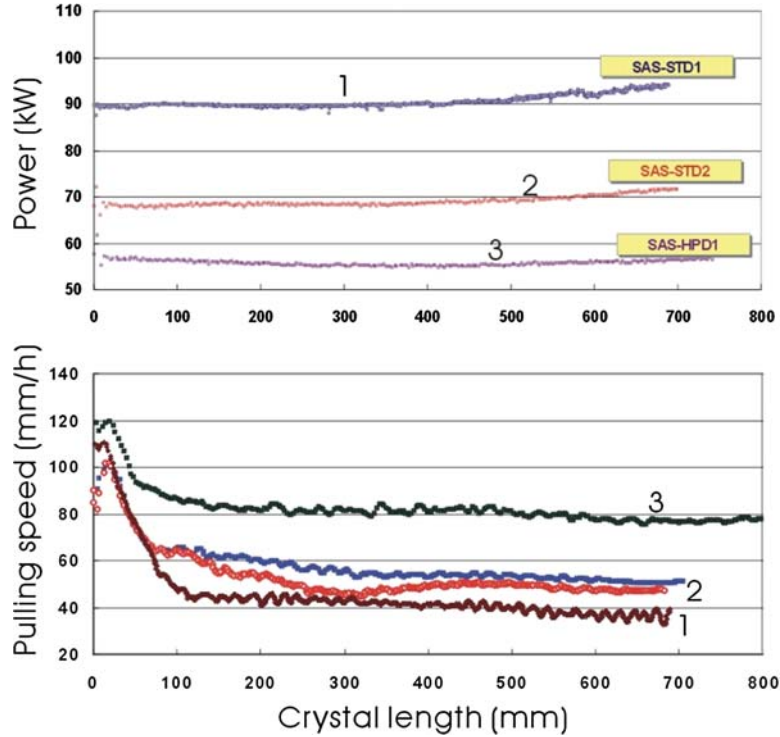
Fig. 2.4. Power (*top*) and pulling speed (*bottom*) histories for different hot-zone designs; the standard design (STD) and high-performance design (HPD) refer to the original default design and the computer-added one

and the high-performance design (HPD) refers to the design screened by computer simulations. As shown, an average growth speed of $80\,\mathrm{mm\,h^{-1}}$ can be achieved. Adding a cooling ring to cool down the crystal can further increase the growth speed, while reducing the interface concavity.

2.2.2 Interface Shape and Thermal Stress

Besides the lower power consumption and the faster pulling speed, an important benefit from the hot-zone design is the small interface deformation. Using the cone is an effective way to reduce the interface concavity. According to simulation, it is found that the cone shape and cone material are the two major factors for the interface control. In general, the cone edge needs to be close to the melt/crystal/gas trijunction line as much as possible [11]. Nevertheless, lowering the cone position increases the risk of melt splashing. The simulation result also reveals that the smaller interface concavity gives a smaller von Miss thermal stress, which is usually concentrated at the trijunction line [11, 21].

In addition to the pulling stage, a proper hot-zone design is also useful for melting and cooling down. For example, during melting down, the crucible position is the lowest, and the radial heating could generate significant thermal gradients and, thus, thermal stress in the crucible. This increases the risk of crucible breakage. The bottom heater is the most effective way to reduce such thermal gradients. However, to save power consumption, the bottom heater is usually turned off during the pulling stage. The power ratio control of both heaters is not easy, but again computer simulation is very useful to optimize the setting. According to our experience, as reported in [11], the additional side and top insulations are less effective. Since the graphite felt is not cheap, using an effective insulation is necessary to reduce the cost.

2.2.3 Argon Consumption and Graphite Degradation

During silicon growth, oxygen is dissolved from the crucible into the melt, forming silicon monoxide (SiO). Carrying SiO away from the melt by argon flow is very important in practice as too much deposition of SiO particles on cooler surfaces, such as the chamber wall, crucible inner wall, and ingot surface, could cause problems when the particles fall down to the melt. The structure integrity is lost, i.e., having dislocations, if the particles get into the growing crystal; then, the growth needs to be restarted and PPH or growth yield is significantly affected. Therefore, the argon flow rate and its path are important to avoid the catastrophe. Further, with the cone, it is observed that argon flow consumption could be significantly reduced. The major reason is that the flow space between the cone and the melt is small and the argon flow across the melt surface becomes faster. Accordingly, the removal of SiO from the melt surface is more effective. The argon flow rate could be reduced from 60 to 15 slpm in our study. This corresponds to 27 cf per kg of Si; the original was 93 cf per kg. The argon flow path is shown by the vector field on the right hand side of Fig. 2.2a. With the cone, near the melt surface, no flow circulation is found, which is believed to be useful in minimizing the falling of SiO particles from the upper cooler surfaces. Nevertheless, the upper part of the cone still has significant SiO deposition. With the top-wall insulation or a composite cone, the deposition is reduced and its position is higher due to the increase of cone temperature.

Besides the argon consumption, the original argon flow path has to run through the graphite heater and SiO reacts with graphite forming silicon carbide. This deteriorates the heater and shortens heater's lifetime. The same is true for graphic susceptor. By redirecting argon to the side insulation, it is found that the heater lifetime, as well as that of the graphite susceptor, could be significantly elongated. Over the project period, heater lifetime is increased to 4,600 h from the original lifetime of 3,000 h. The lifetime of the graphite crucible (susceptor) is increased to 1,500 h, which is almost double that of the original one (880 h). Figure 2.5 shows the photographs of the heater before
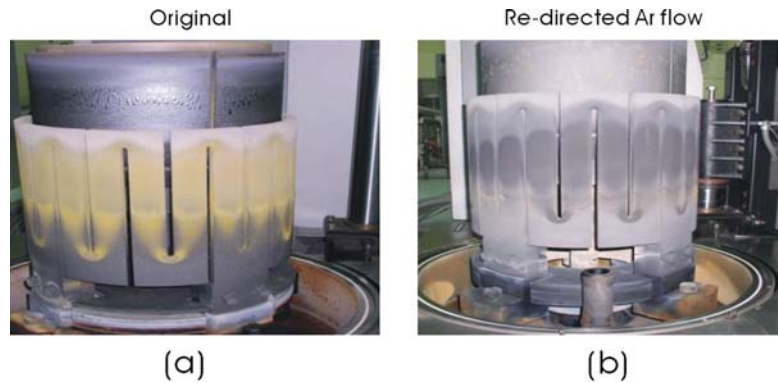
Fig. 2.5. Graphite heaters after growth: (**a**) without redirected argon flow; (**b**) with redirected argon flow

(Fig. 2.5a) and after (Fig. 2.5b) the venting pipe was installed. As shown, as argon is redirected to the side wall, the deposition of SiO on the heater is significantly reduced after crystal growth.

In addition to the cleaner heater, with the cone and the redirected argon flow, the grown crystal surface is found very shining, without any surface oxidation. Figure 2.6 shows the photographs of 5.5 in.- (Fig. 2.6a) and 8 in.-diameter solar ingots. The left two ingots were grown without using the cone. As shown, the colorful oxidation rings are clear. Furthermore, with the cone, the melt leftover in the crucible could be significantly reduced because silicon remains molten near the end of the growth due to the less radiation heat loss. As a result, the wastage of material is reduced significantly. For the same amount of charge, the pulled crystal is, thus, longer.

2.2.4 Yield Enhancement

The yield for dislocation-free growth is the most important factor for PPH. In addition to cost reduction and pulling speed enhancement, a successful pulling without losing structure integrity, i.e., dislocation-free, is extremely important. Once a dislocation is generated during growth, the growth needs to be restarted over, which significantly reduces the production yield. It is believed that particles are responsible for the formation of the dislocations. Therefore, beside the quality of polysilicon raw material, particles due to crucible erosion and SiO deposits peeling off from the top surfaces need to be carefully prevented. This could be done by using a coated crucible and an effective argon venting design. Reducing the argon flow resistance and preventing flow recirculation are found to be useful. The lower crucible temperature due to the lower heating power also reduces silica erosion and particle generation.
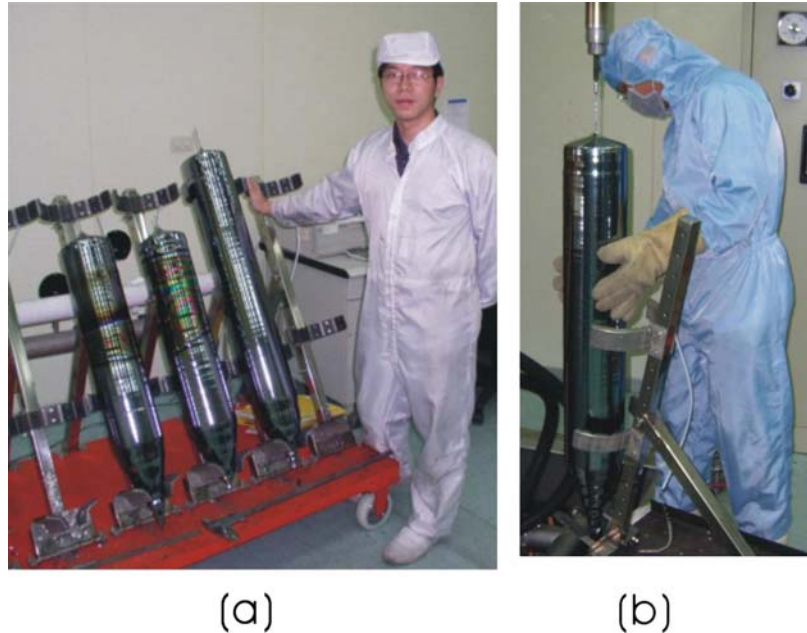
Fig. 2.6. Photographs of grown crystals: (**a**) 5.5-in. diameter; (**b**) 8 in.-diameter; the *left* two ingots in (**a**) were grown from the hot-zone without the radiation shield, so that the oxidation rings are clear on the surface

2.3 Continuous Charge

2.3.1 Multiple Charges

As mentioned, the PPH for 6–8 in.-diameter ingot growth is usually below $2 \, kg \, h^{-1}$, while HEM mc-Si casting can easily reach $3–4 \, kg \, h^{-1}$. The main reason is that a batch charge for HEM is up to 240–300 kg, while a typical charge for a Cz puller, such as Kayex 6000 for 6–8 in. ingot growth, is much less than 100 kg. Therefore, to increase PPH, one has to either increase the charge by using a larger crucible or use continuous charging. Since the traditional crystal pulling is a batch process, the chamber for holding the crystal has a limited length. Therefore, continuous charging is difficult. An alternative is to have multiple charges. In other words, after a crystal is pulled out and removed, without cooling down, the new material can be fed from the feeder. In SSI, this kind of feeder has been used, and the PPH for 6 in.-diameter ingots has been pushed to $1.7 \, kg \, h^{-1}$ [12], and ten crystals could be pulled out from one silica crucible. A similar design has also been adopted for semiconductor applications. Figure 2.7 shows a typical Kayex 150 puller with the installation of the feeder and the recharge tank. Typically, the feeder requires granular or small-chunk polysilicon. This kind of multiple charges can save the time for cooling down and, thus, improve PPH. Since several crystals can be pulled
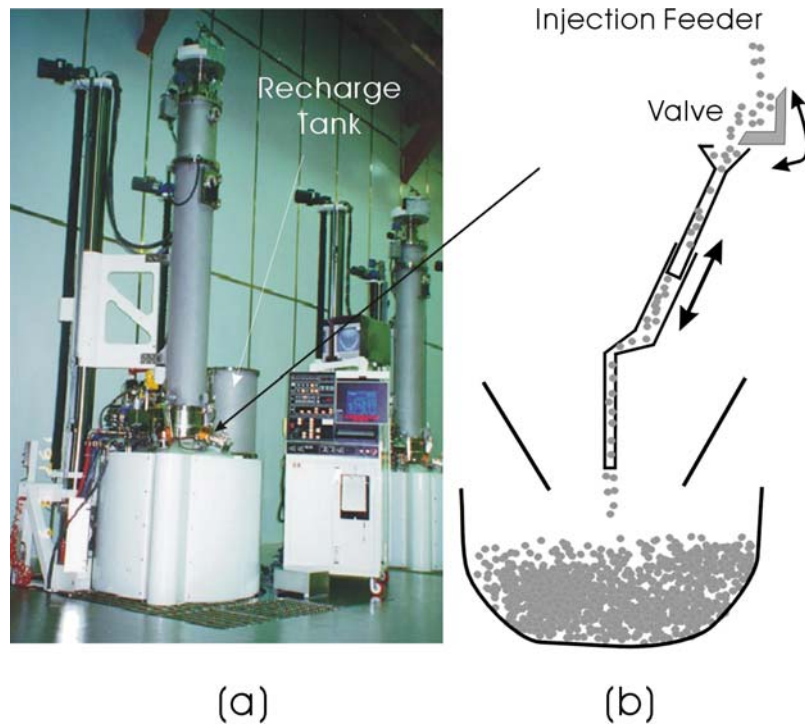
Fig. 2.7. Recharge system for a Kayex 150 puller: (**a**) photograph showing a recharge tank; (**b**) the feeder design (*top*) and the feeding of granular silicon (*bottom*) (Curtsy of Taisil Electronic Materials Inc., Taiwan)

out from one crucible, the crucible cost per kg silicon is greatly reduced. Typically, five crystals (100–150 kg each) can be pulled out from a 22 in.-diameter crucible for semiconductor applications. If such a puller is used for solar ingot with a proper hot-zone design for a high pulling speed, a PPH comparable to HEM casting can be anticipated.

For semiconductor applications, the problems of using multiple charges are metal contaminations during recharge and impurity accumulation in the crucible. The former problem can be resolved by a careful design of the feeder and the material used. However, for impurity accumulation, one has to use high-purity granular polysilicon. Fortunately, for solar-grade silicon, both problems are greatly relieved because of the lower purity requirement. The improvement of PPH further reduces the specific energy consumption (kWh/kg). In SSI, with multiple charges, overall specific energy saving is over 51% [7]. In SAS, before the project, the electricity consumption was $59.1\,\mathrm{kWh\,kg^{-1}}$. After the hot-zone optimization and using multiple charges, the electricity consumption was reduced to only $17.4\,\mathrm{kWh\,kg^{-1}}$ for 5.5 in.-diameter ingots. For 8-in.

silicon, this figure is even lower due to the high PPH; the power consumption during growth needs to be below $65\,\text{kW}$.

2.3.2 Coated Crucible

The quartz crucible is a major cost for solar-grade ingot production, because no cheaper crucibles are available for PV applications. The production of quartz crucibles is quite tedious. The outer layer of the quartz crucible, the so-called bubble layer, needs to be less dense to make the crucible a good insulator, while the inner layer has to be prepared with a denser and stronger amorphous structure. During crystal growth at high-temperature, the devitrification of silica forms crystobalite and it is often detached from the crucible surface and cause dislocations in the growing crystal. For multiple charges, due to the long time operation, the situation is even worse. Therefore, a special coating on the inner crucible surface is necessary. Typically, a dense barium silicate coated layer is used [13]. In this GE patent, barium oxide is used as a good devitrification promoter that helps forming a uniform dissolution layer on the crucible inner surface during crystal growth. Hence, particle generation is reduced. There are also other methods to improve the crucible's inner surface for reducing erosion and particle generation [14]. Of course, if other materials, such as Si_3N_4-coated carbon [22] can be used or the crucible could be reused, and the cost could be further reduced. Again, carbon contamination remains a great concern.

2.3.3 Large Size and Continuous Growth

As discussed in (2.1), the increase in the crystal thermal gradient can increase the pulling rate. However, the gradient (G_s) needs to be kept constant over the entire interface during the whole growth period, and cannot be too high for thermal-stress reason. In addition, crystal quality usually decreases with the increasing cooling rate $(G_S V)$. Therefore, the highest pulling rate is usually below $100\,\text{mm}\,\text{h}^{-1}$ for Cz silicon, and about $30\,\text{mm}\,\text{h}^{-1}$ for HEM mc-Si casting. Moreover, thermal instability often occurs at the edge of the interface due to the larger radial cooling. Hence, as a general rule, to ensure thermal stability and a planar interface, the ratio of volume to surface must be as large as possible [23]. Of course, the availability of large and reliable silica crucibles and furnaces at an affordable price has to be considered. The cost of graphite heaters and elements cannot be ignored as well. In addition, from the investor point of view, the higher capital investment somehow discourages the use of large pullers for cheaper products. Therefore, large pullers, such as Kayex 150 or higher models, have not yet been used for solar ingot production.

However, the cost for equipments and parts increases rapidly with the size. Therefore, without increasing the diameter for an economic ingot production, a continuous process should be considered seriously in the near future. In fact, among the available crystal growth techniques for PV applications,

Cz and HEM are the only batch processes. Others, such as edge-defined film-fed growth (EFG), are continuous. Semicontinuous Cz, i.e., using multiple charges, has been widely used. Recently, the electromagnetic continuous pulling (EMCP) process [24] combining the advantages of cold crucible melting (no crucible consumption and low-pollution) with those of continuous casting has been proposed for PV silicon. Similarly, ingot growth using a square die with a continuous feeding could be a feasible process. The floating-zone technique can also be useful. In fact, Topsil's PV-FZ silicon ingots are available in the market; the solar cell conversion efficiency could be greater than 22% easily. Thanks to the high thermal gradients and crucible free of the FZ technique, its PPH can be very high. However, the pulling of mc-Si by the Cz method could be an interesting consideration; the effort for seeding and keeping structure integrity is removed. Otherwise, the use of a long crucible is a simple way to increase PPH. The same is true for HEM. Furthermore, the less puller stations for the same amount of ingot production also imply the lower personal cost.

2.4 Crystal Quality Improvement

Finally, since crystal quality is directly related to solar cell efficiency, it has to be taken into account for the overall PV cost. In general, the sc-Si ingot is pulled in the <100> direction and this is preferred in the alkaline texturing for the inverted pyramids during solar cell fabrication. Also, because (111) slip planes are oblique to the growth direction, dislocations generated can propagated outward to the crystal surface leading to a dislocation-free ingot. Such an advantage allows the dislocation-free ingot to be pulled at an extremely high pulling rate. One of the major indicators for the solar-cell performance of a wafer is the lifetime of minority-carriers. The control of oxygen and carbon contents has been found important to improve the minority-carrier lifetime. Especially, for N-type silicon, oxygen precipitates usually reduce the minority-carrier lifetime due to the formation of the interface traps at the oxide surfaces [25]. Transition metals are detrimental as well [26]. Boron doped P-type silicon has been found to have a severe light-induced degradation due to a recombination-active boron/oxygen complex, as a result of the reaction involving substitutional boron atoms and interstitial oxygen dimers [27]. Although a special 200°C annealing treatment has been proposed to resolve this problem recently [28], the low-oxygen ingots are still preferred in applications. The oxygen content in the grown crystal is affected by many factors. However, crucible temperature is believed to be an important one. With a lower crucible temperature, the oxygen dissolution into the melt is less. Based on the hot-zone simulation [11], we observed that the crucible temperature in contact with the melt decreases with the decreasing power consumption. Therefore, an energy-saving design is favored for the lower oxygen content. In our hot-zone design, the oxygen content has been reduced to

about 17 ppma in the head and 12 ppma in the tail for 5.5 in.-diameter ingots. The average minority-carrier lifetime is longer than 60 μs.

Similar to oxygen, carbon is also detrimental. In Cz silicon growth, carbon is released mainly from the graphite heater and susceptor, as well as raw polysilicon. Therefore, the control of argon flow path is important to reduce carbon contamination. In fact, after redirecting the argon flow, even with a flow rate of 15 slpm, our hot-zone always keeps the carbon content below 0.03 ppma.

In addition to oxygen and carbon, transition metals and types A and B swirls have also negative effect on the minority-carrier lifetime [29]. Therefore, controlling the growth at a high V/G ratio for getting a vacancy-rich ingot [30,31] is helpful. Still, near the crystal shoulder, due to the higher cooling rate there, getting vacancy-rich is difficult, unless an exceptional high pulling rate is used. Accordingly, the oxidation-induced-stacking-fault ring (OISF-ring), which a visible boundary roughly separating the vacancy-rich (inside) and the self-interstitial-rich regions (outside), is often observed in the solar ingot near the shoulder. The lifetime of the minority carriers is also shorter there. Again, with the improved growth speed using a high-performance hot-zone, the grown ingot can be almost vacancy rich, and the portion of interstitial rich is significantly reduced. However, there is always a trade-off on the high growth rate. Because the cooling rate, i.e., VG_S, is proportional to the pulling rate, and the minority-carrier lifetime usually decreases with the increasing cooling rate [29], finding an optimal V/G is necessary for crystal quality.

2.5 Conclusions and Comments

With the dramatic increase of the demand on silicon solar ingots since 2003, the price of the solar silicon has increased rapidly in conjunction with the soaring price of raw polysilicon. Such a demand is believed to continue for another 2 or 3 years. Indeed, this should be an incentive for silicon producers to switch their interest from IC to PV industries. However, it is also a historical trend that the price of solar cells will continue to decrease, and this implies that the production of solar ingots has to face the same challenge of cost reduction. Hot-zone design has been found extremely useful in this aspect. Besides the faster growth and less power consumption, the cost for consumables, such as argon and graphite components, is significant reduced. Crystal quality can also be improved due to the less oxygen and carbon contents, as well as the vacancy-rich growth at the high growth rate. However, there is always a limitation for the hot-zone to improve. Therefore, using multiple or continuous charges is inevitable for production. This includes a better design of the feeder to reduce contamination and preparing small chuck or granular silicon. In addition, a long-life silica crucible or its substitute is required; a reusable crucible is preferred.

Meanwhile, the high-productivity DS mc-Si casting appears as a strong competitor to Cz ingot pulling. As a result, the market share of sc-Si in the PV industry continues to be deprived by mc-Si. Although the higher mechanical strength of the single crystals is believed to be a unique advantage for thinner solar wafers, say $100\,\mu$m or less, in the future, the slicing technology continues to improve for better yield. Therefore, the share shrinkage of single crystal silicon seems to be inevitable. Furthermore, the requirement of a dislocation-free growth remains a critical factor for the yield of a single crystal, even though its solidification speed can be several times faster than that for DS. This situation could be even worse with low-grade raw polysilicon. Therefore, pulling polycrystalline silicon or continuous casting may not be an unrealistic idea for Cz crystal growers to consider in the future. Again, the grain size, defect, and contamination control, as that in DS, remains a great challenge for Cz mc-Si to have a comparable solar cell efficiency as its single crystals.

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Crystal Growth of Silicon for Solar Cells
(Eds.)K. Nakajima; N. Usami
2009, XIV, 255 p. 160 illus., 6 in color., Hardcover
ISBN: 978-3-642-02043-8