SOLAR SILICON PART II

The requirement for a drastic increase in deliveries of solar-grade silicon requires revision of traditional production methods and equipment, especially furnaces. Part II this month covers thermochemical refining and ingot production. Part I last month showed how induction furnaces can significantly increase the volume of production.

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The earlier generation of furnaces and silicon processing techniques, designed for small volume semiconductor devices, cannot satisfy the growing demand for solar grade silicon. The semiconductor furnace industry is trying to scale up equipment, but the resistive radiant heating elements and construction materials in these furnaces can deliver a power density of about 4 to 7 W/cm² of surface area, limiting the heating/melting rate of silicon.

However, induction furnaces can deliver heat directly or indirectly into a mass of liquid silicon metal with power densities up to 30 W/cm², with controlled stirring of the liquid metal, allowing faster silicon production on a much larger scale. This makes induction furnaces a preferred choice for the next generation of thermal equipment for solar-grade silicon production.

This article shows how polysilicon is produced via the Siemens process and the fluidized bed process, then describes the production of single crystal and multicrystalline ingots.

Siemens process

In the Siemens process, high-purity silicon rods are exposed to trichlorosilane at 1150°C. The trichlorosilane gas decomposes and deposits additional silicon onto the electrically heated silicon rods, enlarging them according to chemical reactions such as:

$$2HSiCl_3 \rightarrow Si + 2HCl + SiCl_4$$

Silicon produced from this and similar processes is called polycrystalline silicon. Because of the high resistivity of the silicon seed rods, the Siemens process requires two power supplies – one for preheating the rods into a conductive state, and the second for superheating the rods by conduction. Most of the energy from the hot silicon rods is radiated into water-cooled bell jars covering the Siemens reactor.

Fluidized bed purification

In the fluidized bed process, pure silicon pellets are grown from tiny pure silicon seeds into polysilicon granules in a high-temperature reaction vessel. This process was developed by the Ethyl Corp., which proposed to use silicon fluoride as a precursor material to produce silane, SiH_4. Silicon fluoride is a waste byproduct of the huge fertilizer industry, which produces tens of thousands of tons of silicon fluoride every year.

After distillation of the silicon fluoride into silane, the SiH_4 is thermally decomposed to polysilicon. In this process, silicon seed particles are introduced into a fluidized bed sustained by a gas stream of silane and hydrogen. The silicon from the decomposed silane gas attaches to the particles, which grow to granule size during their free fall to the bottom of the reactor. A graphic representation of a fluidized bed reactor is given in Fig. 1.

The fluidized bed process offers some significant advantages compared to the Siemens process. The energy losses and hence the energy consumption are considerably reduced because the decomposition operates at a lower temperature, and cooling the bell jar is not required. Another advantage is that large reactors may be constructed and operated continuously, reducing further the capital and operating costs. The end products are small granules of polysilicon that may have some advantages, such as when continuous feeding into the customer's process is needed.

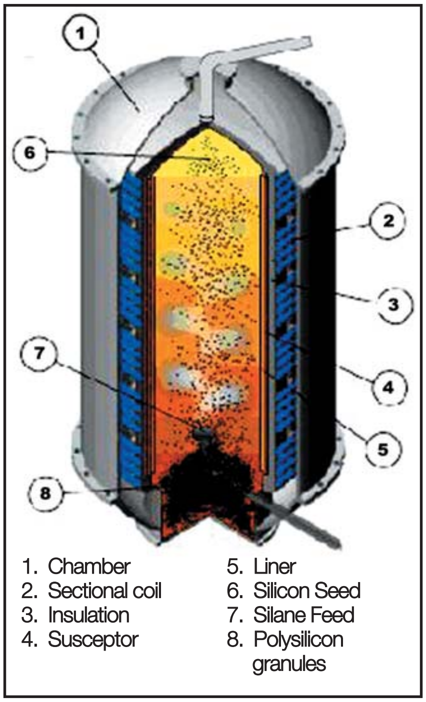

Fig. 1 — Fluidized bed purification of silicon.

Induction heating of the reactor chamber allows the construction of a large polysilicon production

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facility with an internal volume of 3.5m^3. The FB reactor includes a patented multi-section coil with real-time commutation of induction power along the height of the reaction chamber that produces the specified temperature profile. The FB process with induction temperature controls significantly increases the yield of polysilicon. A reactor of this design was started up a decade ago, and has produced thousands of tons of high-purity silicon.

Solar silicon ingots

The material for solar cells is produced in the form of monocrystalline or polycrystalline ingots. These ingots are then sliced into thin wafers that serve as substrates for solar cells. Alternatively, silicon may be produced in thin ribbons of hollow thin-wall polygons, or deposited as a thin layer on a transparent glass or organic transparent film.

- **Single crystal ingots:** Silicon wafers made from monocrystalline silicon have the highest efficiency of conversion of solar energy into electricity, up to 25%. Single-crystal ingots are pulled from the main bath using the Czochralsky Process (CZ), shown in Fig. 2. In this technology, a small seed rod of pure silicon is inserted into the surface of the molten silicon and slowly withdrawn through a die. The die rotates relative to the molten bath, or the molten bath may be rotated relative to the die. Either way, a monocrystalline billet is formed.

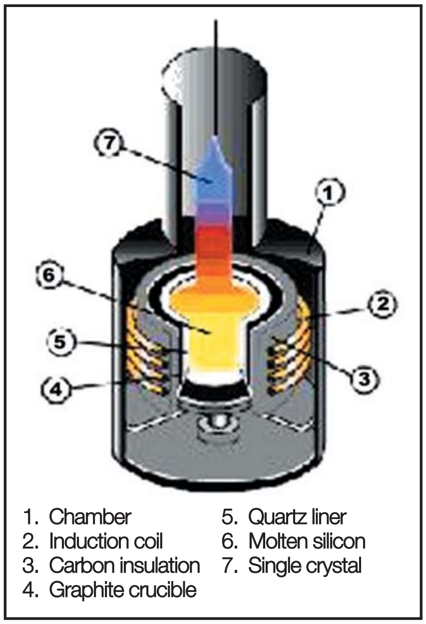

Fig. 2 — Czochralsky method of pulling single crystal silicon ingot.

A variation of the Czochralsky method produces a silicon ribbon pulled through a slot die. Two or more seed rods may be involved, utilizing a capillary effect. This method allows the growth of sheets, hollow cylinders, or thin-wall hollow polygon shapes.

Solar wafers typically 156 x 156 mm are sliced from large ingots. A large crucible is required to make these ingots.

Application of induction heating instead of resistive radiant elements allows the use of larger crucibles, improves furnace reliability, saves energy, and eliminates water-cooled chambers and fragile graphite elements. In addition, the electromagnetic field can counteract the thermal flow in the molten silicon, resulting in a less turbulent bath.

- **Multicrystalline ingots:** Multicrystalline ingots are produced via directional solidification of silicon in quartz-lined crucibles. One method of production is known as sectional coil control.

This method allows the silicon ingot to slowly solidify from the bottom of the induction furnace to the top without moving the crucible. The induction coil in this furnace consists of several individual sections connected to the induction power supply by means of a patented electronic switch.

Each section is sequentially powered, and the electromagnetic field heats the molten silicon in the crucible inside the coil from the bottom, top, and on the sides, as shown in Fig. 3. After a while, the bottom coil is disconnected from the commutation sequence, so that power no longer flows to the lower part of the crucible, and the silicon begins to freeze in the bottom.

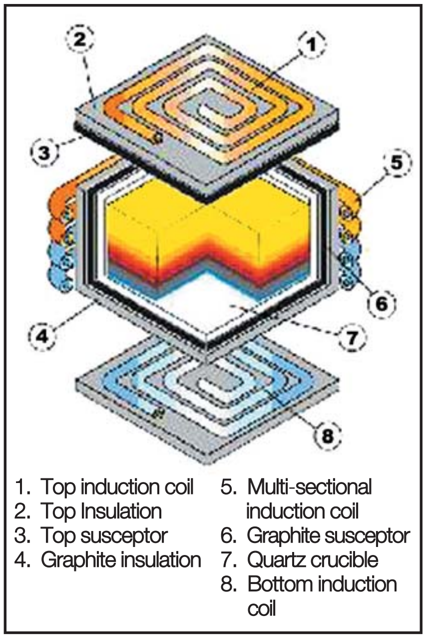

Fig. 3 — Directional Solidification - Sectional Coil.

The lower turns are progressively excluded from the power commutation sequence and the next portion above the bottom solidifies. Gradually, one by one, power to the sections of the coil is turned off, allowing the next slice of silicon in the crucible to solidify. As the process continues, all silicon in the furnace freezes, and the impurities are collected on the top surface.

This method can be combined with settling of heavy inclusions if the hot bath is initially kept for a while in a quiescent state, to allow the heavy particles to precipitate to the bottom.

Multicrystalline ingots as large as 690 mm x 690 mm in cross section may be grown in total cycle times of 56 hours. The best efficiency of small cells, with sophisticated directional solidification processing, is 18.6%. Typical large production cell efficiencies are 13% to 14%, with good consistency.

Induction heating and melting technologies will allow the production of solar grade silicon ingots in significantly larger quantities while requiring less energy. Because most of the high cost of silicon is in the processing, production of larger batches at higher production rates and with less manual interaction will help to meet the expanding needs of the solar cell industry.

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