processes with Cz-Si can therefore use high-efficiency processes with smaller process windows that require well-defined starting material.

Cz technology is mature and cost-effective. Equipment and processes for semi-automated growing of crystals are commercially available so that several Cz pullers can be run by a single operator. Owing to the robust making of the machines, many Cz growers more than 20 years age are still in production.

The ingot can be pulled in a defined <100> orientation. This is a big economic advantage since the solar cell process can use this crystallographic property to homogeneously texture solar cells with a very cost-effective wet chemical etching step. By anisotropic etching, a surface structure with random pyramids is built that couples the incoming light very effectively into the solar cell. This effect together with the usually higher diffusion length of Cz crystals gives rise to the increased efficiency of Cz-Si solar cells compared to similarly processed mc-Si cells.

There exists a high potential for increasing the net pulling speed, that is, the productivity of a puller by a clever design of the hot zone, by sophisticated recharging concepts of Si in the hot crucible and by tuning the growth recipe to the optimum pull speed. Here the PV industry is in the novel position that it can neglect most specifications that are required in the microelectronic industry.

This is possible since the PV specifications are strongly reduced in the number of required parameters in contrast to microelectronic material. A PV specification "simply" focuses on the maximum productivity, a minority-carrier diffusion length of the material that should be exceeding the cell thickness and a shallow *p*-type doping that leads to a specific resistivity between 0.3 and 10 Ωcm, depending on the fabricated solar cell type.

One of the main disadvantages of Cz crystallisation of silicon is the fact that square cells are best suited to built a highly efficient solar module, whereas Cz ingots have a round cross section. In order to use both the crystal and the module area in the best manner, the ingots are usually cut into a pseudosquare cross section before they are cut into wafers. Additionally, the tops and tails of the ingots cannot be used for wafer production. The cropped and slapped materials, that is, tops and tails and so on, are then fed back into the growth process again.

The equipment and the basic principle for Cz pulling is shown in Figure 6.1. The Cz equipment consists of a vacuum chamber in which feedstock material, that is, polycrystalline silicon pieces or residues from single crystals, is melted in a crucible and a seed crystal is first dipped into the melt. Then the seed is slowly withdrawn vertically to the melt surface whereby the liquid crystallises at the seed. High vacuum conditions can be used as long as the melt weight is small (<1–2 kg), but with larger melts (often more than 30 kg) only pulling under argon inert gas stream is practicable. Owing to the reduced argon consumption, the argon pressure is set in the 5 to 50 mbar regime in the PV industry, whereas in the microelectronic industry, atmospheric pressure is also used.

After the silicon is completely molten, the temperature of the melt is stabilised to achieve the required temperature to lower the seed into the melt. The temperature must be chosen so that the seed is not growing in diameter (melt too cold) or decreasing in diameter (melt too hot). In PV the seed is usually <100>-oriented, is monocrystalline and