ribbon and foils and allow these new-generation technologies to become market leaders in silicon wafer production. Technology description, the status of each of the growth approaches and the barriers for each of the technologies to overcome in order to remain competitive are the topics of the following sections.

6.5.1 Process Description

The ribbon technologies that have been proposed over the past three decades and that have survived till the commercial manufacturing and R&D phases (Table 6.3) may be grouped into two basic approaches: "vertical" and "horizontal" growth (pulling) methods. The latter category is further subdivided into methods in which either a substrate is used to assist in the formation of the crystal or foil or those that do not use any substrate material. The horizontal methods refer not so much to the geometrical aspects related to the ribbon-pulling direction as to the disposition of the temperature gradients, which act at the interface and influence growth characteristics. The EFG, WEB and STR methods are examples of the vertical method category, while both the RGS foil and the SF methods grow crystals in a horizontal-pulling configuration with the aid of a substrate. The term "foil" is used interchangeably with wafer, but here we use it to refer more specifically to the RGS wafer to distinguish a unique aspect: the wafer is crystallised upon contact with a substrate, and is then detached and the substrate material recycled.

Ribbon/foil growth techniques have historically been evaluated in a number of variants and modifications of the techniques listed in Table 6.3. Successes and failures in many of these variants often spawned new processes or led to evolution and modifications in old variants. A bibliography and descriptions of the techniques and a detailed historical perspective of the many variant ribbon technologies that have been pursued can be found in the endnote [42] and in References [43, 44].

Fundamental differences exist in the heat transfer and the interface temperature gradients during growth for these two general categories of ribbon and foil production methods. These lead to very different process limits in several important areas: the capacity, or throughput potential in a single furnace configuration, crystallite or grain nucleation characteristics and the pulling speed. The speed is constrained as a consequence of the thermoelastic stress acting on the crystal during growth. The pull speed and stress affect the defect density and electronic quality. For example, for the vertical techniques – WEB, EFG and STR – the crystal growth direction and dominant heat transfer of latent heat from the interface are both parallel to the pulling axis of the ribbon and essentially perpendicular to the growth interface. The latent heat conducted along the ribbon is radiated to the environment. The pulling speed and the interface growth velocity are the same. For RGS and SF, crystals nucleate on the substrate and grow nearly perpendicular to the substrate-pulling direction, while the growth interface tends to be angled towards the pulling axis of the substrate. Thermal conduction of latent heat from the growth interface is augmented in the direction perpendicular to the pulling axis, that is, through the thickness of the ribbon, because of conduction into the substrate. This augmented heat removal allows very high ribbon production rates, whereby low interface growth rates, v_I, are realised with high pull rates, v_P, that is,

$$v_P = v_I / \cos(\theta)$$