the wafer. Growth rates from 4 to 9 m/min have been demonstrated. One example was an 8.6-cm-wide foil, 300-μm thick, grown at 6.5 m/min.

An important goal in the R&D phase of RGS has been to make a substrate that can be reused. After cooling, the silicon foil may be separated from the substrate by stresses arising from differences in thermal expansion between substrate and silicon. Experimentation with coated foils is in progress and offers the most promise in providing a cost-effective reusable substrate. Thicknesses between 100 and 500 μm have been grown. By working with the lower thermal gradients in the foil thickness direction, but still large enough for rapid growth, fluctuations in the pulling speed and gradient only affect the foil thickness slightly [55].

SF. The details of the SF process are proprietary. The silicon crystal is grown in a thin layer directly upon either an insulating or a conducting substrate, with a barrier layer that promotes nucleation [56]. In the case of an insulating substrate, the barrier layer must also 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 provided 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 the active part of the solar cell. The grown polycrystalline silicon layer is made very thin ($\ll$100 μm), thus reducing the amount of silicon required. Currently, layers of 20-μm thickness are under development. A variety of substrate materials have been used including steel, ceramics and graphite cloth [56, 57]. It is necessary that the barrier layer prevent the transport of impurities from the substrate into the silicon. The barrier layer allows wetting and nucleation during growth. It should also act to electrically passivate the back surface and have a high optical reflectivity.

An insulating barrier layer has been reported that promotes growth of large columnar grains (greater than 1 mm) through the thickness of the grown SF silicon film [56]. As-grown films on coated ceramic substrates exhibit very low diffusion lengths of less than 10 μm. The new barrier layer and the substrate result in longer diffusion lengths, 20 to 40 μm, and the silicon has an improved response to phosphorous gettering.

6.5.2 Productivity Comparisons

Ribbon crystal growth technology for production of silicon wafers has been historically faced with the evaluation of the trade-off between bulk electronic quality and throughput (productivity per furnace). The choice of crystal growth conditions is made on the basis of wafer cost parameters and the premium imposed by the marketplace on solar cell efficiency. Material quality that can translate into high solar cell efficiencies has always been a primary market driver guiding ribbon growth process development. Ribbon wafers have inherently lower wafer production costs than those obtained from directionally solidified and cast ingots, or Cz boules, because ribbon growth avoids the large material losses due to sawing, which exceed 50% of the starting feedstock. The ribbon geometry has an additional cost advantage in that high levels of radiative cooling allow very rapid pulling rates. On the other hand, the higher wafer cost for the cast ingot or Cz boule production methods demand that these products maintain an advantage in bulk electronic quality, and higher solar cell and module efficiencies, in order to stay competitive with respect