propagate into the ribbon centre. In both EFG and STR, the grain dimensions typically are large compared to the ribbon thickness and the as-grown diffusion length, and the charge collection and solar cell efficiency are minimally influenced by grain boundary recombination.

For SF and RGS, the substrates provide the dominant nucleation sites for crystals. The grains usually are columnar and extend through the ribbon thickness with dimensions that can be made large compared to the diffusion length with proper adjustments of the pulling speed and interface inclination.

Fast movement of the solid–liquid interphase reduces the ability of the freezing process to segregate impurities to the melt. This is represented in Table 6.5 together with the crystalline aspect and the dislocation density of the different technologies.

Stresses produced by thermal gradients during growth generate most of the intra-granular dislocations in ribbon material. In the best quality EFG material, it has been shown that the loss in background current is highly correlated with the dislocation density and not grain boundaries [60]. It is not clear if the intrinsic qualities of the dislocations act as recombination centres or if the associated impurity cloud is responsible. Dislocations decorated with SiO_x precipitates have been reported to limit the lifetime in WEB [61] and RGS material [62]. Recent photoluminescence studies suggest similar causes for dislocation recombination activity in EFG material [63].

A critical parameter for solar cell efficiency is the ribbon thickness. As shown by Bowler and Wolf [64], an optimum thickness for peak efficiency occurs. This thickness is dependent on the fabrication technique and material properties, including front and back surface recombination velocities, minority-carrier lifetime and base resistivity among other parameters. For a "typical" $n^+ pp^+$ structure with a 200-µm diffusion length, L_d, a back surface field and a single layer anti-reflection coating, the optimum thickness region consists of a broad peak near 80 µm (Figure 6.27) as calculated using PC-1D [65]. For a 100-µm L_d the optimum thickness peaks at about 50 µm and for a 400-µm L_d it is near 120 µm. A front surface recombination velocity of 10^5 cm/s is assumed.

Table 6.5 Comparison of silicon ribbon material characteristics. In all cases the columnar grains extend through the thickness of the ribbon. An equilibrium segregation coefficient of $k_0 \sim 10^{-5}$ is typical of the most detrimental impurities for ribbon bulk lifetime

Material	Crystallinity	Dislocation density [1/cm²]	Effective segregation	Thickness [µm]
EFG	Columnar grains in growth direction	10^5–10^6	$k_0 < k_{eff} < 10^{-3}$	250–350
WEB	Single (111) face central twin planes	10^4–10^5	$k_0 < k_{eff} < 10^{-3}$	75–150
STR	Columnar grains in growth direction	5×10^5	$k_0 < k_{eff} < 10^{-3}$	100–300
SF	Columnar grains through thickness	10^4 to 10^5	$k_{eff} < 1$	50–100
RGS	Columnar grains through thickness	10^5–10^7	$k_{eff} < 1$	300–400