run. Throughput will eventually become an issue. However, in-line CVD processes have been developed, for example, in the manufacture of amorphous silicon solar modules.

13.6.2 Module Fabrication

Soda lime float glass is the substrate material that so far has given the best results in terms of both performance and reproducibility. It fulfills criteria on cost (3 $/m^2 for 4-mm-thick glass in large volumes), smoothness, and stability, so it is well suited for commercial production. One limitation that needs to be addressed in the development of production processes is that soda lime glass starts to soften above 500°C. At the same time, the best PV properties of $Cu(InGa)Se_2$ are achieved at growth temperatures above 500°C. Plastic deformation due to glass softening is not acceptable in a module-production process and careful optimization of the time–temperature profile is needed to minimize the deformation.

Flexible substrate materials are attractive both for the possibility to make a lightweight flexible product with advantages for certain applications and for the possibility to deposit the thin-film materials in roll-to-roll processes, which are potentially cost-advantageous. Such roll-to-roll processing of semiconductor thin films was originally demonstrated with evaporation of CdS for solar cells [209]. The substrate materials that have shown promising results are polyimide, titanium, and steel [68, 69]. The drawbacks of polyimide are low-temperature tolerance, since the best polyimide films readily available can only withstand 400 to 450°C, and high thermal expansion. The main drawback of titanium and steel is their conductivity, which means that an electrically isolating layer is needed in order to allow monolithic series-interconnection of the cells. Such an isolation layer is not easy to make without local defects that will cause shunting of the cells. For these flexible substrate materials, sodium has to be supplied separately.

An essential cost advantage with thin-film PV modules as compared to silicon wafer–based PV modules is the possibility of monolithic interconnection. This allows modules to be fabricated directly, instead of first making cells followed by tabbing and stringing to make the series interconnection as required for silicon-wafer solar cells. A typical monolithic interconnection is illustrated schematically in Figure 13.22. The most common way to make the patterning is by using laser ablation for the Mo patterning (P1) and mechanical scribing for the two subsequent patterning steps (P2 and P3).

The final fabrication steps include attachment of electrical wires and buss bars. These are metal stripes that can be soldered, welded, or glued to contact areas near the edges of the substrate plates. Before lamination with a front cover glass, the thin-film layers are removed from the outer rim of the substrate plate in order to improve the adhesion to the lamination material, which is usually ethylene vinyl acetate (EVA). Edge sealing and framing finishes the product, but can be omitted for some applications.

13.6.3 Module Performance

The evolution of record efficiencies as reported from the certified measurement labs is displayed in Figure 13.23. The module efficiencies lag behind the cell efficiencies but follow the same basic trend. There are additional losses associated with making