though other substrate materials including metal or plastic foils have also been used and may have processing advantages.

The most promising deposition methods for the commercial manufacture of modules can be divided into two general approaches that have both been used to demonstrate high device efficiencies and in pilot scale manufacturing. The first approach is vacuum coevaporation in which all the constituents, Cu, In, Ga, and Se, can be simultaneously delivered to a substrate heated to 400 to 600°C and the $Cu(InGa)Se_2$ film is formed in a single growth process. This is usually achieved by thermal evaporation from elemental sources at temperatures greater than 1000°C for Cu, In, and Ga. The second approach is a two-step process that separates the delivery of the metals from the reaction to form device-quality films. Typically the Cu, Ga, and In are deposited using low-cost and low-temperature methods that facilitate uniform composition. Then the films are annealed in a Se atmosphere, also at 400 to 600°C. The reaction and anneal step often takes longer time than formation of films by coevaporation due to diffusion kinetics, but is amenable to batch processing. High process rate can be achieved by moving continuously through sequential process steps or with a batch process whereby longer deposition or reaction steps can be implemented by handling many substrates in parallel.

13.3.1 Substrates

Soda lime glass, which is used in conventional windows, is the most common substrate material used for $Cu(InGa)Se_2$ since it is available in large quantities at low cost and has been used to make the highest efficiency devices. $Cu(InGa)Se_2$ deposition requires a substrate temperature (T_{SS}) of at least 350°C and the highest efficiency cells have been fabricated using films deposited at the maximum temperature, $T_{SS} \approx 550°C$, which the glass substrate can withstand without softening too much [64]. The glass is electrically insulating and smooth, which enables monolithic integration into modules.

The soda lime glass has a thermal expansion coefficient of 9×10^{-6}/K [64], which provides a good match to the $Cu(InGa)Se_2$ films. The glass composition typically includes various oxides such as Na_2O, K_2O, and CaO. These provide sources of alkali impurities that diffuse into the Mo and $Cu(InGa)Se_2$ films during processing [18], producing the beneficial effects discussed in Section 13.2. However, a process that provides a more controllable supply of Na than diffusion from the glass substrate is preferred. This can be achieved by blocking sodium from the substrate with a diffusion barrier such as SiO_x or Al_2O_3. Then sodium can be directly provided to the $Cu(InGa)Se_2$ growth process by depositing a sodium-containing precursor layer onto the Mo film [65, 66]. Commercially available soda lime glass may also contain significant structural defects that can adversely impact module production [67]. Borosilicate glass does not contain the alkali impurities and may have fewer structural imperfections but has a lower thermal expansion coefficient, 4.6×10^{6}/K [64], and is more expensive.

Substrates such as metal or plastic foils have advantages over glass substrates owing to their light weight and flexibility, which will be discussed in Section 13.6. $Cu(InGa)Se_2$ devices have been demonstrated with different metal and high-temperature polyimide substrates [68, 69].