devices, with and without CBD–CdS, in the majority of the R&D groups. Typically, ZnO:Al films are deposited by radio frequency (rf) magnetron sputtering from ceramic ZnO:Al_2O_3 targets with 1 or 2 weight% Al_2O_3. In large-scale manufacturing, dc sputtering from ceramic targets is favored since it requires simpler equipment and offers higher deposition rates [155].

Reactive dc sputtering from Al/Zn alloy targets has also been used in the fabrication of Cu(InGa)Se_2/CdS devices with the same performance as with rf sputtered ZnO:Al [156]. The use of Zn/Al alloy targets allows lower costs than ceramic ZnO:Al_2O_3 targets, but reactive sputtering requires very precise process control owing to the so-called hysteresis effect [157] so that optimal optoelectronic properties are achieved only within a very narrow process window. Deposition rates in 4 to 5 nm/s range have been achieved.

Chemical vapor deposition (CVD) provides another deposition option and is used by one commercial manufacturer of Cu(InGa)Se_2 modules to deposit ZnO [158]. The reaction occurs at atmospheric pressure between water vapor and diethylzinc and the films are doped with fluorine or boron.

ALCVD deposition of ZnO has also been tested [159]. The atomic layer by atomic layer growth gives very low deposition rates, but the surface-controlled growth process gives uniform layers within a wide process window concerning reactant flow. This allows large batches to be processed, resulting in a reasonable throughput in spite of the limited growth rate.

As with the Mo back contact, the requirements for sheet resistance of the transparent contact layer will depend on the specific cell or module design. Typically, small area cells use layers with 20–30 Ω/□, while modules may require 5–10 Ω/□. In either case, the sheet resistance is usually controlled by the layer thickness.

13.4.6 Buffer Layers

It is common practice to use a buffer layer of undoped high-resistivity (HR) ZnO before sputter deposition of the TCO layer. Depending on the deposition method and conditions, this layer may have a resistivity of 1–100 Ω cm compared to the transparent contact with 10^{-4}–10^{-3} Ω cm. Typically, 50 nm of HR ZnO is deposited by rf magnetron sputtering from an oxide target.

The gain in performance by using an HR ZnO buffer layer in ordinary devices with CBD–CdS is related to the CdS thickness [156, 160, 161]. One explanation of the role of a ZnO buffer layer is given by [160] as resulting from locally nonuniform electronic quality of the Cu(InGa)Se_2 layer that can be modeled by a parallel diode with high recombination current. The influence of these regions on the overall performance is reduced by the series resistance of the HR ZnO layer. This series resistance has a negligible effect on the performance of the dominant parts of the device area. A related explanation would attribute the local areas with poor diode characteristics caused by pinholes in the CdS layer, which create parallel diodes with a Cu(InGa)Se_2/ZnO junction. In this case improved diode quality due to the ZnO buffer would improve overall performance. Either case is consistent with the observation that a beneficial effect from the ZnO buffer is not observed when the CBD–CdS layer is thick enough [161].