13.2.5 Substrate Effects

The effects of the substrate on the properties of thin-film polycrystalline Cu(InGa)Se$_2$ can be classified into three categories: (1) thermal expansion, (2) chemical effects, and (3) surface influence on nucleation.

It can be assumed that after growth, when the substrate and film are still at the growth temperature, the stress in the Cu(InGa)Se$_2$ film is low. The cooling down from growth temperature imposes a temperature change of about 500°C, and if the thermal expansion of the substrate and Cu(InGa)Se$_2$ is different stress will be built up in the film. The thermal expansion coefficient for CuInSe$_2$ is around 9×10^{-6}/K in the temperature interval of interest, which is similar to that of soda lime glass. A CuInSe$_2$ film deposited on a substrate with a lower thermal expansion coefficient, such as borosilicate glass, will be under increasing tensile stress during cooldown. Typically, such films exhibit voids and microcracks [50]. When the thermal expansion coefficient of the substrate is higher than that of the film material, like for polyimide, it will result in compressive stress in the thin-film material, which may lead to adhesion failures.

The most important effect of the soda lime glass substrate on Cu(InGa)Se$_2$ film growth is that it supplies sodium to the growing chalcopyrite material. It has been clearly shown that this effect is distinct from the thermal expansion match of soda lime glass [60]. The sodium diffuses through the Mo back contact, which also means that it is important to control the properties of the Mo [61]. The resulting microstructure of Cu(InGa)Se$_2$ is clearly influenced by the presence of Na with larger grains and a higher degree of preferred orientation, with the (112) axis perpendicular to the substrate. An explanation for this effect when high concentrations of Na are present has been proposed by Wei *et al.* [38].

There is a wide range of preferred orientation between different growth processes, in spite of similar device performance. One reason for this variation is most likely the different properties of the surfaces on which the chalcopyrite material nucleates. A comparison between Cu(InGa)Se$_2$ grown on normal Mo-coated substrates and directly on soda lime glass shows that a much more pronounced (112) orientation occurs on glass, in spite of no difference in the Na concentration, as measured in the films afterwards [18]. Further, the preferred orientation of the Cu(InGa)Se$_2$ film has been shown to be correlated to the orientation of the Mo film [62] or an (InGa)$_2$Se$_3$ precursor layer [63].

13.3 DEPOSITION METHODS

A wide variety of thin-film deposition methods has been used to deposit Cu(InGa)Se$_2$ thin films. To determine the most promising technique for the commercial manufacture of modules, the overriding criteria are that the deposition can be completed at low cost while maintaining high deposition or processing rate with high yield and reproducibility. Compositional uniformity over large areas is critical for high yield. Device considerations dictate that the Cu(InGa)Se$_2$ layer should be at least 1 μm thick and that the relative compositions of the constituents are kept within the bounds determined by the phase diagram, as discussed in Section 13.2.1. For solar cell or module fabrication, the Cu(InGa)Se$_2$ is most commonly deposited on a molybdenum-coated glass substrate,