However, after more than 25 years of research and development of $CuInSe_2$, manufacturing has only recently moved past the pilot-production stage and has not demonstrated any cost advantages. A fundamental question must be asked: what needs to be done to ensure that $Cu(InGa)Se_2$ solar cell technology reaches its potential for large-scale power generation?

Part of the answer is to address the critical need for the accelerated development of new manufacturing technology including improved deposition equipment and processes based on well-developed engineering models. Also, new diagnostic and process-control tools will have to be developed. This requires fundamental materials and device knowledge to determine what properties can be measured in a cell or module fabrication process that can act as reliable predictors of final performance. Better processes, equipment, and control based on a more solid knowledge base can directly translate to higher throughput, yield, and performance.

There is also a critical need for continued improvement in the fundamental science of the materials and devices [222, 223]. Significant improvements in efficiency will only come from increased V_{OC} so the chemical and electronic nature of the defects that limit it, and their origin, must be understood. This can contribute to a comprehensive model for the growth of $Cu(InGa)Se_2$, relating processing parameters to defect formation, junction formation, and device limitations. In addition, a fundamental understanding of the role of sodium and the nature of the grain boundaries and free surface needs to be developed. A greater understanding of the role of the CdS layer and the chemical bath process might enable alternative materials that do not contain cadmium and have wider band gap to be utilized with greater efficiency and reproducibility.

A second fundamental question to be asked is: what might be the breakthroughs that could lead to the next generation of thin-film $Cu(InGa)Se_2$-based solar cells?

Further development of wide band gap alloys to enable cells to be made with $E_g \geq 1.5$ eV without any decrease in performance will have several benefits for module fabrication and performance as discussed in Section 13.5. In addition, development of a cell with $E_g \approx 1.7$ eV is a prerequisite for tandem cells based on the polycrystalline thin films to be developed. A monolithic tandem cell has the potential to attain efficiencies of 25% or more. The $CuInSe_2$ alloy system is ideally suited for such a structure since a $CuInSe_2$ cell with $E_g = 1.0$ eV would make an ideal bottom cell with any of the alloys that increase band gap to 1.7 eV for the top cell. Even if a high-efficiency wide band gap cell is developed, such a structure will require the development of a transparent interconnect between the top and bottom cells and improvements in cell structure or low-temperature processes to allow the bottom cell to survive the subsequent processing of the top cell.

Low-temperature processing of the $Cu(InGa)Se_2$ layer without loss of efficiency in the final solar cell can have significant additional benefits. With lower substrate temperature, alternative substrate materials, like a flexible polymer web, can be utilized. In addition, lower T_{SS} can reduce thermally induced stress on the substrate, allowing faster heat-up and cooldown, and decrease the heat load and stress on the entire deposition system. Similarly, there may be significant cost and processing advantages to a cell structure that enables the use of a $Cu(InGa)Se_2$ layer much less than 1 μm.