line is successfully completed. In good single crystal Si cells, the manufacturing yield is 95%. Many supposedly cheap technologies find their Achilles' heel in the low yield.

Finally, the module fabrication requires interconnecting and encapsulating the cells. These steps also have room for some cost reduction. The use of cheaper materials may help somewhat, as well as better automation, better module interconnection, and integration designs.

1.9 THIN FILM PROGRESS AND CHALLENGES

One might ask "why develop a totally different semiconductor technology for photovoltaics when Si is so well established?". The simplest answer is "to achieve lower cost and improved manufacturability at larger scales than could be envisioned for Si wafer-based modules." In fact, we have already defended our belief that Si technology, very important in the next decades, will not be able to reach the ultimate goals required for mass worldwide penetration of photovoltaics (Section 1.5). What were the disadvantages of c-Si that led to the early investigation and eventual commercialization of alternatives? It was recognized early in the development of photovoltaics that Si crystals were expensive and slow to grow. It was also recognized that of all the viable semiconductors, Si would require the greatest thickness to absorb sunlight, due to its unique optical properties. Si is the most weakly absorbing semiconductor used for solar cells because it has an indirect band gap while most of the other semiconductors have a direct band gap (see Chapter 3 for a more complete explanation of direct and indirect band gaps). Therefore, at least ten times more crystalline Si is needed to absorb a given fraction of sunlight compared to other semiconductors like GaAs, CdTe, $Cu(InGa)Se_2$, and even other forms of Si such as a-Si. Thicker semiconductor material means higher material volume but also a higher quality material because of the longer paths that the high-energy electrons excited by the photons must travel before they are delivered to the external circuit to produce useful work. All this leads, as seen before, to high material cost. In addition, we mention that, presently, much of the Si-PV industry relies on buying scrap material from the electronics industry. As photovoltaics' demand grows, the supply of scrap material might become insufficient (see Chapter 5).

It was recognized almost as early as c-Si PV cells were developed in the 1950s that other semiconductors could make good solar cells. Most of them exist in a form called thin films. When they are fabricated into useful devices, they are so thin that they must be deposited on a foreign material called a substrate for mechanical support like a layer of paint on a piece of wood or the reflective metal coating on glass to form a mirror. A framework for analyzing the material properties, device structures, and manufacturing issues unique to thin-film solar cells (TFSC) was developed [64] since they differ considerably from Si wafers. Throughout the 1970s, progress in Cu_2S/CdS solar cells led to the development of new theories to explain the device performance, new methods of materials processing, and new concepts in semiconductor device manufacturing [65, 66]. Between 1981 and 82, four thin-film technologies demonstrated the ability to cross the magical 10% efficiency barrier, thus becoming candidates for serious consideration: Cu_2S/CdS [67], a-Si [68], $CuInSe_2$/CdS [69], and CdTe/CdS [70]. (It is an inexplicable fact in this business that 10% efficiency seems to suddenly confer respectability and status to any PV technology.) Of these four TFSC technologies, Cu_2S/CdS would soon be