

ent electronics 'killer apps' are admittedly either not yet well-defined or are presently unrealizable due to current limitations in transparent electronics or in a requisite auxiliary technology. However, this topical ordering inversion is meant to be intentionally provocative. Since transparent electronics is a nascent technology, we believe that its development will be most rapidly and efficiently accomplished if it is strongly application-driven, and if it is undertaken in a parallel fashion in which materials, devices, circuits, and system development are pursued concurrently. Hopefully, such a product-driven concurrent development strategy will lead to rapid technology assessment, the identification of new and most-likely unexpected applications, and an expeditious commercial deployment of this technology.

## 1.2 Pre-history

Two primary technologies which preceded and underlie transparent electronics are briefly overviewed. These topics are transparent conductive oxides (TCOs) and thin-film transistors (TFTs).

### 1.2.1 Transparent conducting oxides (TCOs)

TCOs constitute an unusual class of materials possessing two physical properties - high optical transparency and high electrical conductivity - that are generally considered to be mutually exclusive (Hartnagel et al. 1995). This peculiar combination of physical properties is only achievable if a material has a sufficiently large energy band gap so that it is non-absorbing or transparent to visible light, i.e.,  $> \sim 3.1$  eV, and also possesses a high enough concentration of electrical carriers, i.e., an electron or hole concentration  $> \sim 10^{19}$  cm<sup>-3</sup>, with a sufficiently large mobility,  $> \sim 1$  cm<sup>2</sup> V<sup>-1</sup>s<sup>-1</sup>, that the material can be considered to be a 'good' conductor of electricity.

The three most common TCOs are indium oxide In<sub>2</sub>O<sub>3</sub>, tin oxide SnO<sub>2</sub>, and zinc oxide ZnO, the basic electrical properties of which are summarized in Table 1.1. All three of these materials have band gaps above that required for transparency across the full visible spectrum.

Note that although the TCOs listed in Table 1.1 are considered to be 'good' conductors from the perspective of a semiconductor, they are actually very poor conductors compared to metals. For example, the conduc-

tivities of tungsten W, aluminum Al, and copper Cu, are approximately 100,000, 350,000, and 600,000 S cm<sup>-1</sup>, indicating that the best In<sub>2</sub>O<sub>3</sub> conductivity (for indium tin oxide or ITO) is about a factor of 10 to 60 lower than that of a typical integrated circuit contact metal. The low conductance of TCOs compared to metals has important consequences for both TCO and transparent electronics applications, some of which are explored in this book. The theoretical absolute limit of the conductivity for a TCO has been estimated to be 25,000 S cm<sup>-1</sup> (Bellingham 1992).

**Table 1.1. Electrical properties of common transparent conducting oxides (TCOs) Conductivities reported are for best-case polycrystalline films.**

Material	Bandgap (eV)	Conductivity (S cm <sup>-1</sup> )	Electron concentration (cm <sup>-3</sup> )	Mobility (cm <sup>2</sup> V <sup>-1</sup> s <sup>-1</sup> )
In <sub>2</sub> O <sub>3</sub>	3.75	10,000	$>10^{21}$	35
ZnO	3.35	8,000	$>10^{21}$	20
SnO <sub>2</sub>	3.6	5,000	$>10^{20}$	15

Returning to Table 1.1, notice that all three of the TCOs included in this table are n-type, i.e., conductivity is a consequence of electron transport, and that the electron carrier concentration is strongly degenerate, i.e., the electron density exceeds that of the conduction effective band density of states by an appreciable amount (Pierret 1996; Sze and Ng 2007). All of the well-known and commercially relevant TCOs are n-type. p-type TCOs are a relatively new phenomenon and their conductivity performance is quite poor compared to that of n-type TCOs. To a large extent, the poor conductivity of p-type TCOs is due to the very low mobility of these materials, typically less than  $\sim 1$  cm<sup>2</sup> V<sup>-1</sup>s<sup>-1</sup>, compared to mobilities in the range of  $\sim 10$ -40 cm<sup>2</sup> V<sup>-1</sup>s<sup>-1</sup> for n-type TCOs.

The n-type mobilities indicated in Table 1.1 are quite small compared to those representative single crystal silicon materials and devices, which range from  $\sim 250$ -1,500 cm<sup>2</sup> V<sup>-1</sup>s<sup>-1</sup>. However, this mobility comparison between TCOs and single crystal silicon is a bit misleading since single crystal silicon mobility is not usually specified at doping concentrations as large as those typical of TCOs. In fact, it is reported that single crystal silicon mobility is independent of doping concentration above  $\sim 10^{19}$  cm<sup>-3</sup>, with an electron mobility of  $\sim 90$  cm<sup>2</sup> V<sup>-1</sup>s<sup>-1</sup> and a hole mobility of  $\sim 50$  cm<sup>2</sup> V<sup>-1</sup>s<sup>-1</sup> (Baliga 1995). A low mobility at high carrier concentrations is, to a large extent, a consequence of intense ionized impurity scattering associated with high doping concentrations (Hartnagel et al. 1995).