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The Transparent Conductive Oxides In2O3:Sn, SnO2:X, TiO2:X and ZnO:X: An Intercomparison Study of Electronic and Optical Properties

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In this work the transparent conductive oxides indium oxide (In_2O_3), tin oxide (SnO_2), titanium oxide (TiO_2), and zinc oxide (ZnO) are reviewed. While In_2O_3, SnO_2, and ZnO are already commercially used on a large scale in flat panel displays, thin film solar cells and low emissivity window glass coatings, TiO_2 is currently still under development. These TCO materials are n-type, wide bandgap semiconductors that can be doped up to high carrier concentrations ($N > 10^{21}$ cm^{-3}) making it degenerate semiconductors, i.e. metal-like. The lowest resistivities ($>1 \cdot 10^{-4}$ Ωcm) are achieved with doped indium oxide, mostly doped with tin.
The maximum carrier concentrations that can be achieved in these TCOs is about the same. The significantly different resistivities of these four oxides are due to their different electron mobilities μ; the highest values being reported for ITO ($\mu > 100$ cm^2 /Vs). The physical processes, limiting the mobility at such very high carrier concentrations ($>5 \cdot 10^{20}$ cm^{-3}) are not yet fully understood. The main scattering processes are discussed for every of the oxides.
All TCOs are highly transparent from the UV to the NIR spectral range. In the IR spectral range, depending on the carrier concentration, absorption by free electrons takes place. By using hydrogen as a dopant, indium oxide with very high electron mobility can be deposited, thus reducing the free carrier absorption in the IR.
Research and development is going on to replace In_2O_3 by ZnO, which is much cheaper (abundance ≈ 120 ppm). SnO_2 is already used on a large scale for window glass coatings and also for thin film solar cells, based on CdTe. SnO_2 and TiO_2 are chemically very resistive, a property that is still awaiting a wider application.

Keywords
transparent conductive oxides
wide bandgap semiconductors
charge carrier transport
carrier scattering