

TECHNOLOGICAL CHALLENGES FOR TRANSPARENT CONDUCTORS

Roy G. Gordon

Harvard University Chemical Laboratories, 12 Oxford Street, Cambridge, MA 02138, USA *

Transparent conductors (TCs) have a variety of properties that can limit their performance in various applications. These properties include their optical and electronic behavior: optical transparency, electrical conductivity, plasma wavelength, ultraviolet absorption edge, work function, conductivity type; factors affecting device fabrication: synthesis temperature, thermal stability, resistance to plasmas, ease of etching; and factors affecting their usage: chemical durability, surface roughness, hardness, mechanical flexibility, cost and toxicity. For each of these properties, particular devices are identified for which that property is particularly important in limiting its performance. Some possible methods to improve these limiting properties are also discussed.

1. INTRODUCTION

A few materials, mostly oxides of tin, indium and/or zinc, are both electrically conductive and transparent. These TCs have many important applications in modern technology, such as energy efficient windows, displays, anti-static coatings.¹

There is no such thing as a perfectly transparent conductor. Real materials transmit less than 100% of light incident on them and have non-zero electrical resistances. There are also limits on the wavelength ranges over which TCs are transparent, reflective or absorbing, on their work functions, and on the type of charge carriers (electrons or holes). During the formation of a useful device incorporating TCs, synthesis temperature, thermal stability, resistance to plasmas and ease of etching may be important. The end user of TCs may find other properties relevant: chemical durability, smoothness, hardness, flexibility, cost and toxicity.²

For some applications of TCs, their non-ideal behavior has insignificant impact on the overall performance of a device in which they are only one component. In other cases, the properties of the TC may limit the capabilities of the device, so that improvements in the TC could have important practical benefits. In the latter type of situation, further research on TCs has the most potential impact.

The following sections deal in turn with the optical and electrical properties of TCs, factors related to building TCs into devices, and issues affecting the end uses of these devices.

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2. OPTICAL AND ELECTRONIC PROPERTIES

2.1 More transparent and conductive TCs

High transparency to visible light and high electrical conductivity are of course the two key features of a transparent conductor. There is generally a tradeoff between these properties. For example, making a thinner layer increases the transparency, but also increases the electrical resistance. Particular applications may require a certain minimum transmission and the lowest resistance that can be attained with that minimum transmission. For example, an automobile windshield is required by law (in the US) to have a minimum transmission of 70%. Having the lowest possible electrical resistance then minimizes the time required to defrost the windshield (for a fixed maximum available voltage).

It is important to have an appropriate figure of merit for measuring how well each TC material can meet these pairs of requirements. A quantitative measure of the performance of transparent conductor materials is the ratio of the electrical conductivity σ to the visible absorption coefficient, α ,

$$\sigma/\alpha = -\{R_s \ln(T+R)\}^{-1} \quad (1)$$

in which R_s is the sheet resistance in ohms per square, T is the total visible transmission, and R is the total visible reflectance. σ/α is thus a figure of merit for rating TC materials.³ A larger value of σ/α indicates better performance of the material as a TC.

Table I. Figure of Merit for Some Transparent Conductors

Material	Sheet Resistance	Visible Absorption	Figure of Merit
	(ohms/square)	(1-T-R)	(inverse ohms)
ZnO:F	5	0.03	7
Cd ₂ SnO ₄	7.2	0.02	7
ZnO:Al	3.8	0.05	5
In ₂ O ₃ :Sn (ITO)	6	0.04	4
SnO ₂ :F	8	0.04	3
ZnO:Ga	3	0.12	3
ZnO:B	8	0.06	2
SnO ₂ :Sb	20	0.12	0.4
ZnO:In	20	0.20	0.2

Figures of merit for some transparent conductors are given in Table I. The values are for the best samples that we have prepared in our laboratory by CVD at atmospheric pressure, except for the indium oxide value, which is the best that we have measured for a commercially available film, and cadmium stannate values, which are taken from the literature.⁴

These results show that the fluorine-doped zinc oxide and cadmium stannate have the best figure of merit of these transparent conductors. If the electrical and optical properties of a transparent conductor were independent of film thickness, then the figure of merit σ/α would not depend on film thickness, unlike others that have been proposed.⁵ In fact, properties of transparent conductors do depend somewhat on film thickness, for example because they depend on crystalline grain size, which usually increases with film thickness. Thus the figure of merit generally increases with film thickness. The film thicknesses of the samples reported in Table II were chosen to be typical of those needed for low-resistance applications such as solar cells.

The results in Table I show that fluorine doping gives superior performance compared to metallic dopants, in both zinc oxide and tin oxide. A theoretical understanding of this advantage of fluorine can be obtained by considering that the conduction band of oxide semiconductors is mainly derived from metal orbitals. If a metal dopant is used, it is electrically active when it substitutes for the primary metal (such as zinc or tin). The conduction band thus receives a strong perturbation from each metal dopant, the scattering of conduction electrons is enhanced, and the mobility and conductivity are decreased. In contrast, when fluorine substitutes for oxygen, the electronic perturbation is largely confined to the filled valence band, and the scattering of conduction electrons is minimized.

A theoretical upper limit to the figure of merit may be estimated from the Drude transport theory of electrons in metals⁶ to be given by

$$\sigma/\alpha = 4\pi^2\varepsilon_0c^3n(m^*\mu)^2\lambda^{-2}e^{-2} \quad (2)$$

where μ is the mobility and m^* is the effective mass of the conduction electrons. n is the refractive index of the film, λ is a visible wavelength of light, ε_0 is the permittivity of free space, c is the speed of light in vacuum, and e is the electronic charge. The refractive index of oxide TCs are close to 2.0 in the visible region. Thus the highest figure of merit will be obtained from the material with the highest product of mobility and effective mass. For zinc oxide⁷, tin oxide⁸ and cadmium stannate,⁹ m^* is close to 0.3 m , where m is the free electron mass. Thus most of the variation in figure of merit is due to differences in mobility. It is worth noting that the free electron concentration does not enter into the figure of merit.

The electron mobility is determined by the electron scattering mechanisms that operate in the material. First of all, there are scattering mechanisms, such as scattering of electrons by phonons, that are present in pure single crystals. In tin oxide¹⁰ and zinc oxide¹¹, these scattering mechanisms lead to mobilities about $250 \text{ cm}^2\text{V}^{-1}\text{sec}^{-1}$ at low doping levels, typically around 10^{16} cm^{-3} . Practical TCs need much higher doping levels, usually over 10^{20} cm^{-3} , in order to operate at reasonable thicknesses. For these high doping levels, scattering by the ionized dopant atoms becomes another important scattering mechanism that alone limits the mobility to less than about $90 \text{ cm}^2\text{V}^{-1}\text{sec}^{-1}$.¹² In the presence of both these scattering mechanisms, the mobility is limited to a value $(250^{-1} + 90^{-1})^{-1} = 66 \text{ cm}^2\text{V}^{-1}\text{sec}^{-1}$. This maximum mobility is lowered still further by other scattering mechanisms, such as grain boundary scattering, present in polycrystalline thin films. The best TC films, ZnO:F and Cd₂SnO₄, have been prepared with mobilities in the range 50 to 60 $\text{cm}^2\text{V}^{-1}\text{sec}^{-1}$, closely approaching the theoretical upper limit. Thus there is not much room for finding a better TC material, unless it has a rather different electronic structure that yields a larger product of effective mass and mobility.

2.2 Thinner TC's

In some applications of TC's, it is critical that the TC be as thin as possible. For example, in high-resolution displays, the required etched patterns in the TC create height variations in the device. To keep the topography as smooth as possible, the thinnest possible TC is desired. In this case, the important material parameter is the electrical resistivity, some typical values of which are given in Table II.

Table II. Approximate minimum resistivities and plasma wavelengths for some TCs.

Material	Resistivity ($\mu\Omega\text{-cm}$)	Plasma wavelength (μ)
Ag	1.6	0.4
TiN	80	0.7
In ₂ O ₃ :Sn	100	>1
Cd ₂ SnO ₄	130	>1
ZnO:Al	150	>1
SnO ₂ :F	200	>1.5
ZnO:F	400	>2

Thus the thickness needed to reach a given sheet resistance increase in the order

$$\text{Ag} < \text{TiN} < \text{In}_2\text{O}_3:\text{Sn} < \text{ZnO}:\text{Al} < \text{SnO}_2:\text{F} < \text{ZnO}:\text{F}.$$

Because of it has the lowest resistivity, silver films can form the thinnest TC layers. However, the fragile silver layers must be protected against abrasion and chemical attack. The protective layers, usually of zinc oxide, increase the effective thickness of silver-based TCs.

These protective layers also reduce the reflection from the silver, so they cannot be omitted from a high-transmission TC even in a protected environment. The next most conductive material, titanium nitride, usually has significant optical absorption, and also has higher resistivity in very thin films. Thus TiN is not commonly used as a thin TC. Tin doped indium oxide (ITO), $\text{In}_2\text{O}_3:\text{Sn}$, is most commonly used as a thin TC in high-resolution displays.

The search for a TC thinner than ITO has occupied a great deal of effort in recent years, particularly in Japan. So far, these efforts have not been successful.

2.3 Wider range of transmitted, reflected or absorbed wavelengths

Energy-conserving window coatings represent the largest areas of TCs currently produced. The free electrons provide the spectral selectivity that is the basis of low-emissivity coatings. For wavelengths longer than the plasma wavelength, the TC reflects radiation, while for shorter wavelengths, the TC is transparent. Usually the plasma wavelength is in the infrared, so infrared (heat) waves are reflected, while shorter-wavelength visible light is transmitted. In a cold climate, it is desirable to transmit all of the solar radiation into a building, so the plasma wavelength should be about 2 microns or larger. In a hot climate, air-conditioning costs are minimized if the plasma wavelength is about 0.7 microns, so solar near-infrared heat (wavelengths from about 0.7 to 2 microns) is reflected and kept out of the building. The values of plasma wavelengths are given in Table II for typical TC materials. The plasma wavelengths for the semiconducting oxides can be adjusted by changing the dopant concentrations, within the ranges shown.

For cold climates, any of the oxide TCs can be adjusted to have a long enough plasma wavelength by reducing the doping concentration. Silver and titanium nitride, being metals, have fixed plasma wavelengths, and thus cannot be optimized for cold climates.

Silver, titanium nitride and ITO can have optimum plasma wavelengths for hot climates, whereas the other oxides cannot be doped to high enough electron concentrations to be optimum for hot climates. It would be an important advance to find a way to dope one of the less expensive oxides, tin oxide or zinc oxide, to high enough electron concentrations to provide window coatings with optimum performance in hot climates.

Another application of TCs is to screen out unwanted ultraviolet radiation that can cause fabrics or art work to fade and other materials to degrade. Undoped zinc oxide strongly absorbs UV wavelengths less than about 400 nm, while transmitting the full visible spectrum. Thus the optical properties of ZnO are ideal for this application. However, when the ZnO is doped to high conductivity, the absorption edge is shifted further into the ultraviolet (Moss-Burshtein effect) so that it no longer absorbs the near UV wavelengths. Some electrochromic devices (windows,

mirrors and displays) are subject to UV degradation, so it would be advantageous to find a TC that combined high conductivity and UV screening.

2.4 TC's with larger or smaller work functions

When the function of a TC includes injection of electron or holes into a device, the work function of the material can play an important role in its suitability. Injection of electrons typically requires a low work function, while injection of holes requires a high work function. Well-characterized values of work function can be hard to obtain, because of its sensitivity to the preparation of the surface. Work function values can be measured by a Kelvin probe, by photoemission in vacuum, by electrochemical methods in contact with solutions, or by analysis of the electrical characteristics of solid-state devices containing the material. Of course, the values from these different sources may differ because the material is contacting a vacuum, liquid or a solid, respectively, in these different methods of measurement. Nevertheless, the trend of values is usually the same in all three cases. Table III gives some values of work functions determined by photoemission.

Table III. Work Functions of some Transparent Conductors¹³

TC	Work Function (eV)	Electron Concentration (cm ⁻³)
ZnO:F	4.2	2×10^{20}
ZnO	4.5	7×10^{19}
In ₂ O ₃ :Sn	4.8	$> 10^{20}$
SnO ₂ :F	4.9	4×10^{20}
ZnSnO ₃	5.3	6×10^{19}

Zinc oxide has the lowest work function of these TC materials, and thus it makes the lowest electrical resistance contact to n-type semiconductors. Zinc oxide is commonly used as the contact material for n-type amorphous silicon layers in thin-film solar cells. Zinc stannate has the highest work function, so it is predicted to form an even lower resistance contact to p-type semiconductors than tin oxide, which is more commonly used for this purpose.

If a new TC material with a lower or a higher work function could be found, the efficiency of optoelectronic devices, such as solar cells and light-emitting diodes, might be improved.

2.5 TC's with p-type conductivity

The commonly-used TC's all have n-type semiconductority. TC's with p-type conductivity could be used to form transparent p-n junctions. These could be used to make better active-matrix liquid crystal displays.

Materials under current investigation for p-type conductivity include zinc oxide co-doped with nitrogen and gallium, ZnO:GaN₂. Relatively high hole concentrations (up to $4 \times 10^{19} \text{ cm}^{-3}$) have been reported¹⁴ for ZnO:GaN₂, but the material does not appear to be thermally stable. In contrast, CuAlO₂ is thermally stable (in fact it has only been crystallized at high temperatures).¹⁵ Hole concentrations up to $1.8 \times 10^{19} \text{ cm}^{-3}$ have been achieved in mixed phases of nanocrystalline Cu₂O and CuAlO₂.¹⁶ Other promising p-type TC materials include CuGaO₂,¹⁷ CuInOx¹⁸ SrCu₂O₂,¹⁹ CuScOx,²⁰ CuY_{1-x}Ca_xO₂²¹ and CuLa_{1-x}Sr_xOS.²²

The work function of a p-type TC is likely to be quite high, although no values of work function have been reported for any of them. If very high work functions are in fact found the new p-type TCs, they may be valuable as hole injectors in light-emitting diodes, and as low-resistance contacts to p-type solar cell materials.

3. DEVICE FABRICATION

3.1 Lower synthesis temperature

When TCs are deposited onto a substrate, the temperature of the substrate generally must be maintained at a sufficiently high temperature to develop the required properties in the TC. The required temperatures usually increase in the order In₂O₃:Sn (ITO) < ZnO < SnO₂ < Cd₂SnO₄. Thus ITO is often preferred for deposition on thermally sensitive substrates, such as plastic, while cadmium stannate requires very refractory substrates (special high-melting glass) to develop its best properties. SnO₂:F can be deposited on ordinary soda-lime glass, but the best electrical and optical properties are developed when a diffusion barrier is placed between the SnO₂:F and the glass. Silica (SiO₂) is most commonly used as the barrier layer between soda-lime glass and tin oxide, even though silica is only partially effective in blocking the transport of sodium. The silica layer usually serves a second purpose, that of eliminating the interference colors that would otherwise be shown by the TC film.²³ Alumina is a much more complete barrier against diffusion of sodium.²⁴ ZnO:F can be deposited on soda-lime glass at temperatures that are low enough (from 400 to 500 °C) so that sodium does not diffuse out of the glass and a sodium barrier is not

needed. ZnO:Al and ZnO:B can be deposited in conductive form at temperatures below 200 °C, but ZnO:F from known CVD processes is not conductive at deposition temperatures much below 400 °C. Reduction of deposition temperature without degradation of TC properties would broaden the applicability of any of the TCs.

3.2 Greater thermal stability

High processing temperatures can be needed for later steps in formation of devices. Architectural windows may need strengthening (tempering) by heating to high temperatures followed by rapid cooling. Cadmium telluride solar cells require a high-temperature annealing step to increase the grain size of the CdTe.

TC's often decrease their conductivity and/or transparency when heated to a temperature higher than the highest one encountered during their preparation. This temperature can be the deposition temperature, or a post-deposition annealing temperature. Cadmium stannate is probably the most thermally stable TC currently known. However, it cannot reach its full potential properties without an anneal at temperatures too high for inexpensive soda-lime glass substrates. Tin oxide is also quite thermally stable; however, its resistance can increase on reheating due to diffusion of sodium out of a soda-lime glass substrate. A good transparent diffusion barrier, such as amorphous aluminum oxide, can mitigate this effect. Further increases in the service temperature of TC-coated glass require improvements in the material for the glass substrate, not the TC.

3.3 Stability in plasmas

In forming amorphous silicon solar cells on TC superstrates, the TC is exposed to a plasma containing hydrogen atoms. These plasma conditions rather easily reduce tin oxide, causing an increase in the optical absorption by the tin oxide. Zinc oxide is much more resistant to hydrogen plasma reduction, and may be preferred for applications such as amorphous silicon solar cells.²⁵

3.4 Etching patterns in TCs

For some applications of TCs, such as displays, heaters or antennas, parts of the TC must be removed. Table IV lists some chemicals which may be used to etch TCs. Zinc oxide is the easiest material to etch, tin oxide is the most difficult, and indium oxide is intermediate in difficulty. The CrCl₂ method for etching SnO₂ involves an air-sensitive solution, so it is more common to use the heterogeneous reaction between solid zinc and aqueous acid.

Series-connected thin film solar cells also need to remove the TC along patterns of lines. Removal of tin oxide is usually carried out by laser ablation with visible light. Because zinc

oxide absorbs so little visible light, laser ablation with either UV or IR light should be more effective.

Table IV. Etchants For Transparent Conductors

<i>Material</i>	<i>Etchant</i>
ZnO	Dilute acids
ZnO	Ammonium chloride
TiN	H ₂ O ₂ + NH ₃
In ₂ O ₃	HCl + HNO ₃ or FeCl ₃
SnO ₂	Zn + HCl
SnO ₂	CrCl ₂

4. USE OF TCs

4.1 Greater chemical durability

TCs can encounter corrosive environments during production of devices as well as during their end use. During deposition of amorphous silicon solar cells the hydrogen plasma can reduce tin oxide superstrates. During exposure to the environment, acid rain can etch zinc oxide, and water vapor or sulfur-containing pollutants can tarnish silver. Electrochemical corrosion of TCs can be encountered in electrochromic devices.

There is no one rank order for chemical durability. Rather, each combination of TC and chemical must be considered individually. Tin oxide TC layers are used to protect glass windows from graffiti etched by hydrofluoric acid, while zinc oxide dissolves even in dilute acids. On the other hand, zinc oxide resists reduction by hydrogen plasmas that reduce tin oxide. Despite this advantage, zinc oxide superstrates have not yet replaced tin oxide in amorphous silicon solar cells because higher contact resistance forms between zinc oxide and the subsequently deposited p-type amorphous silicon. This contact resistance problem has now been solved,²⁶ so the efficiencies of a-Si solar cells could be increased by more than 10% by using more transparent ZnO:F in place of SnO₂:F.

Table V. Chemical Stability of TC Materials

Material	Oxidizing Acids	Reducing Acids	Strong Bases	Hydrogen Plasma
Ag	dissolves	stable	stable	
TiN	stable	stable	stable	stable
TiO ₂	stable	stable	stable	stable
In ₂ O ₃ :Sn	dissolves	dissolves		
Cd ₂ SnO ₄		dissolves		

ZnO:Al	dissolves	dissolves	dissolves	stable
SnO ₂ :F	stable	dissolves	stable	reduced
ZnO:F	dissolves	dissolves	dissolves	stable

Electrochromic devices can be particularly prone to corrosion because the TCs are exposed alternately to highly oxidizing and highly reducing conditions during cycles of coloration and bleaching. Titanium dioxide is fairly stable to both highly oxidizing and highly reducing conditions, but is not highly conductive. Composite TCs with a thin outer layer of titanium dioxide might be used to make chemically resistant TCs for electrochromic windows and displays. Table V summarizes this information about chemical stability.

4.2 Harder TCs

The mechanical durability of TCs is related to the hardness of the crystals from which they are formed. Their hardness values may be ranked using Moh's scale, in which higher values represent harder materials.²⁷ Diamond is the hardest material known, with Moh's hardness of 10.

Table VI. Hardnesses of some TCs.

Material	Moh's Hardness
TiN	9
SnO ₂	6.5
Soda-lime glass	6
In ₂ O ₃	~5
ZnO	4
Ag	low

Table VI shows that titanium nitride and tin oxide are even harder than glass, and can be used in applications that are exposed to contact, since all common materials are softer than TiN and SnO₂. Zinc oxide is readily scratched, but can be handled with care. Thin silver films are so fragile that they cannot be touched and can only be used when coated with protective layers. Since only a few substances are harder than TiN (diamond, SiC, boron, Al₂O₃, and a few carbides and nitrides), it is unlikely that a harder TC will be found.

4.3 Smoother hard TC's

Polycrystalline TC's, such as tin oxide and zinc oxide, have rough surfaces. In some applications, such as electrodes for amorphous silicon solar cells, this surface roughness is desirable, since it enhances the collection of photons by the cells, and thus increases their efficiency.

In most other applications, the roughness is undesirable. For example, on low-emissivity windows, surface roughness scatters light, so excessive roughness can reduce the clarity of the

view. If a tin oxide TC surface is rubbed by metal, bits of the metal can adhere to the surface, resulting in an effect called “metal marking”, which looks like a scratch in the coating. The metal “scratch” can generally be removed with acid, but it would be better if the surface were smooth enough to avoid metal marking.

On Xerographic copiers, static charge can build up on the glass surface that holds the document being copied, and degrade the image quality. Tin oxide coatings are used to drain off these static charges, but the roughness of their surfaces can make it harder to clean than bare glass. Thus only a very thin tin oxide coating is deposited in order to minimize its surface roughness. The sheet resistances of these very thin coatings may be higher than optimal for draining the static charges.

On bar-code readers, tin oxide-coated glass is used to increase the durability of their glass windows against abrasion from the products that are slid across the surface. In order to avoid marks from metal products on bar-code readers, the tin oxide surfaces must be polished smooth, adding a costly step to their manufacture. Some bus windows are now protected from scratched graffiti by tin oxide coatings. However, they are then vulnerable to metal marking if vandals discover that they can write on them with metal. Polishing is probably not cost-effective for this application.

Frost can be prevented from forming on an automobile windshield during cold, clear nights by a low-emissivity tin oxide coating on its outer surface. This passive de-icing effect is not used commercially at present because the rough surface of the tin oxide abrades the windshield wipers too quickly.

Roughness on CVD TC surfaces can usually be reduced by lowering the deposition temperature. However, the growth rate and the conductivity of the film are also usually lower, so a tradeoff must be made between these properties and the roughness. Atomic layer CVD might be used to make extremely smooth transparent conductors; however the growth rate and deposition efficiency may be too low to be cost-effective for many large-scale applications.²⁸ Another approach to reducing haze from surface roughness is to overcoat the TC with a glaze with a low melting point, such as a bismuth silicate glass.²⁹

4.4 More flexible TC's

TC's currently in use are brittle ceramics. In some potential applications, it might be advantageous to have TC's that are more tolerant of bending. Organic conductors might fill this need, but conductivity, transparency and durability of organic conductors have usually been too low for most applications. One likely possible application for organic TC's might be in anti-static

flexible packaging for computer chips. Currently, metal-coated (aluminum or nickel) plastic films are used. However, the metal films can become corroded or degraded during storage, so the shelf-life of these materials can be shorter than desired.

4.5 Less expensive TCs

The costs of producing a TC material depend on the cost of the raw materials and the processing of it into a thin layer. The costs of raw materials generally increase in the order:

$$\text{Cd} < \text{Zn} < \text{Ti} < \text{Sn} \ll \text{Ag} \ll \text{In}.$$

Indium is a rare and expensive element that is obtained as a byproduct of mining ores for their content of other metals, such as zinc and lead. There are no “indium mines” because its concentration in minerals is too low to allow economic extraction only for the value of the indium. Thus the supply of indium cannot be increased significantly without a large increase in price sufficient to make “indium mines” profitable.

Costs of the deposition methods typically increase in the following order: atmospheric pressure CVD < vacuum reactive evaporation < magnetron sputtering < low pressure CVD < sol-gel < pulsed laser deposition. This ranking was estimated by considering the lowest-cost product made by each process. For example, APCVD produces the least expensive TC, SnO₂:F low-E window coatings, whose wholesale price is about \$0.50/ft² added to that of the glass substrate.³⁰ Magnetron sputtered ZnO/Ag/ZnO coatings are slightly more expensive to produce, while sputtered ITO coatings are an order of magnitude more costly, ranging in price from about \$3.50 to \$7.00/ft².³¹ Sol-gel antireflection coatings are still more expensive.³²

The speed of the deposition process is very important in the cost. Atmospheric pressure CVD has the highest coating rate, followed by magnetron sputtering. Sol-gel suffers from slow drying steps, and pulsed laser deposition is only suitable for small areas. This ranking of processes can give only a rough comparison of production costs, because many other factors enter into a full economic analysis, including the production volume and the tolerances for variations in properties of the product.

Using toxic elements in TCs increases their cost, because of protections needed for production workers, end users and the environment. Toxicity generally increases in the following order:

$$\text{Zn} < \text{Sn} \sim \text{Ti} \sim \text{In} \sim \text{Ag} \ll \text{Cd}.$$

Zinc is an essential dietary element and is usually not toxic. Tin, titanium, indium and silver metals are generally considered non-toxic, although some of their compounds are toxic. Cadmium and all of its compounds are carcinogens and are thus heavily regulated and prohibited

from some applications. Additional encapsulation may be needed for products containing cadmium, as well as provisions for recycling of the products.

5. CONCLUSIONS

Transparent conductors have limitations in their optical and electronic properties: conductivity, transparency, the wavelength range over which they are transparent, reflective or absorbing, work function and semiconducting type. Other properties may constrain the incorporation of TCs into devices: synthesis temperature, thermal stability, resistance to plasmas and ease of etching. Finally, during use of TCs, other chemical and mechanical properties may be relevant: chemical durability, smoothness, hardness, flexibility, cost and toxicity. The best available TCs for each of these properties are given in Table VII.

The limitations of these materials represent the current state of the art of known TCs. To improve on these properties, researchers will need to discover new materials or better methods for production of these known materials. In some cases these properties may limit the effectiveness of TCs in particular applications. In these cases, research into new TC materials and new fabrication methods could extend the usefulness of these important materials.

Table VII. The best available TCs for each property

Highest transparency	ZnO:F, Cd ₂ SnO ₄
Highest conductivity	In ₂ O ₃ :Sn, TiN, Ag
Longest plasma wavelength	ZnO:F, SnO ₂ :F
Shortest plasma wavelength	In ₂ O ₃ :Sn, TiN, Ag
Best Ohmic contact to n-Si	ZnO:F
Best Ohmic contact to p-Si	SnO ₂ :F
Lowest synthesis temperature	ZnO:B, In ₂ O ₃ :Sn, Ag
Highest thermal stability	Cd ₂ SnO ₄ , SnO ₂ :F
Best resistance to H plasmas	ZnO:F
Most easily etched	ZnO:F, TiN
Best chemical durability	SnO ₂ :F
Textured surface possible	ZnO:F, SnO ₂ :F
Smooth surface possible	In ₂ O ₃ :Sn, TiN, Ag
Deposit on soda-lime glass	ZnO:F, In ₂ O ₃ :Sn
Hardest	SnO ₂ :F, TiN

Most flexible	Ag, organics
Lowest cost	SnO ₂ :F
Least toxic	ZnO:F, SnO ₂ :F
Most Abundant Elements	ZnO:F, TiN

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