New figure of merit for transparent conductors*

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A figure of merit for transparent electrode materials has been defined by $\phi_{TC} = T^{10}/R_s$, where T is the optical transmission and R_s is the electrical sheet resistance. Expressions are derived to predict the transparent electrode properties of a material from its fundamental electrical and optical constants. The performance of thin metal films is compared to semiconducting oxide coatings.

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INTRODUCTION

Transparent thin-film electrodes are assuming increasing practical importance. Specific applications can be accomplished by selecting a suitable material from a number of elements or compounds. The choice of a particular material is, in general, based on a set of performance requirements; these include electrical, optical, and mechanical properties as well as chemical stability. Moreover, raw-material availability will have to be considered if large-scale deployment is anticipated.

Common to all transparent conductor applications is the need for optimizing the electrical and optical coating parameters. Depending on the type of device requiring a transparent electrode, the optical transmission and the electrical conduction of the electrode will have to exceed certain minimum values. Ideally, both parameters should be as large as possible. Their interrelationship, however, excludes, in most cases, the simultaneous achievement of maximum transmission and conduction.

In this paper the question of comparing the performance of transparent conductor materials will be discussed and the problem of defining a meaningful figure of merit ϕ_{TC} analyzed. The dependence of the figure of merit on the film thickness will be evaluated and it will be shown that a properly defined ϕ_{TC} provides a tool for assessing different materials.

TECHNICAL DISCUSSION

The optical and electrical properties of a transparent conductive coating are best characterized by the electrical sheet resistance R_s and optical transmission T. The sheet resistance is defined by

$$R_s = 1/\sigma t, \tag{1}$$

where σ is the electrical conductivity in $\Omega^{-1}\,\text{cm}^{-1}$ and t is the coating thickness in cm. The dimension of R_s is customarily quoted in Ω/square to indicate that it measures the resistance of a square surface area whereby the square area is independent of dimension and absolute value.

The optical transmission is given by the ratio of radiation I_0 entering the coating on one side to the radiation I leaving the sample on the opposite side so that

$$T = I/I_0 = \exp(-\alpha t), \tag{2}$$

where α is the optical absorption coefficient measured in cm^{-1}.

It has been proposed[1] to define a figure of merit F_{TC} by

$$F_{TC} = T/R_s \tag{3}$$

which can be transformed with Eqs. (1) and (2) into

$$F_{TC} = \sigma t \exp(-\alpha t). \tag{4}$$

According to Eq. (4), the figure of merit of a coating with given σ and α is a function of its thickness and achieves a maximum value at t_{max}. This t_{max} can be calculated from

$$\frac{\partial F_{TC}}{\partial t} = \frac{\sigma \exp(\alpha t) - \sigma t \alpha \exp(\alpha t)}{\exp(2\alpha t)} = 0,$$

$$t_{max} = 1/\alpha.$$

Substituting t_{max} into Eq. (2) yields the transmission at maximum F_{TC},

$$T = 1/e = 0.37.$$

The foregoing result demonstrates that the maximum figure of merit, as defined by Eq. (3), occurs at a film thickness which reduces the optical transmission to only 37%. Such a transmission is too low for most transparent conductor applications and a coating absorbing almost two-thirds of the incoming light would be useless.

We are, therefore, confronted with the problem that in evaluating transparent electrodes by F_{TC} one particular electrode could be judged superior over others even though its optical absorption is too high for practical applications. A clearer illustration of this fact is given in Fig. 1 which shows F_{TC} versus film thickness with α and σ as parameters. The values of α and σ cover a range including the leading transparent conducting oxides. Let us compare two coatings each one having, for instance, $\sigma = 10^4\ \Omega^{-1}\,\text{cm}^{-1}$ and $\alpha = 10^3\ \text{cm}^{-1}$ (curve 1). Coating 1 is assumed to be 10^{-3} cm thick while the thickness of coating 2 is 10^{-4} cm. From Eqs. (1) and (2) we calculate for coating 1 a transmission of 37% and 0.1-Ω/square sheet resistance. Although the sheet resistance is excellent, the low transmission imposes a severe restriction on the usefulness of the coating. On the other hand, coating 2 has a 90% transmission and a 1-Ω/square sheet resistance rendering it a superior transparent electrode which could be readily used for every application currently practiced.

Yet, according to Fig. 1, coating 1 has a larger figure of merit than coating 2.

The preceding discussion points to the need for redefining the figure of merit of a transparent conductor. The definition given in Eq. (3) weighs F_{TC} too much in favor of the sheet resistance, thus resulting in a maximum F_{TC} at a comparatively large film thickness. A better balance between transmission and sheet resistance can be achieved if we redefine the figure of merit by

$$\phi_{TC} = T^x/R_s \tag{5}$$

with $x > 1$. Following the procedure outlined for F_{TC}, the film thickness which maximizes ϕ_{TC} is now

$$t_{max} = 1/x\alpha .$$

For practical purposes a judicious selection of the exponent x has to be made. Values of x equal to 10, 20, or 100, for instance, lead at t_{max} to transmissions of 0.90, 0.95, and 0.99, respectively. It appears that $x = 10$ offers the most favorable choice since it simplifies numerical calculations of practical figure of merits In addition, few transparent conductor applications require more than 90% transmission.

The difference between F_{TC} and our proposed figure of merit ϕ_{TC} arises from the added stipulation that the maximum ϕ_{TC} occurs at 90% optical transmission and not at 37%. We now have

$$\phi_{TC} = T^{10}/R_s = \sigma t \exp(-10\alpha t) \tag{6}$$

and

$$t_{max} = 1/10\alpha .$$

The dependence of ϕ_{TC} on film thickness for six combinations of α and σ is shown in Fig. 1. The curves are qualitatively identical to those of F_{TC} but differ numerically. Some helpful information for practical applications can be gained from Fig. 1. It follows that, with a given electrical conductivity, differences in the absorption coefficient become insignificant if low sheet resistances are not required. Comparing, for instance, curves 2 and 5 ($\sigma = 10^3\ \Omega^{-1}\ \mathrm{cm}^{-1}$) we see that at $t = 10^{-5}$ cm the figure of merits are almost equal even though the optical absorption coefficients differ by a factor 10. Both films have 100-Ω/square sheet resistance. At lower sheet resistances, of course, differences in α are important.

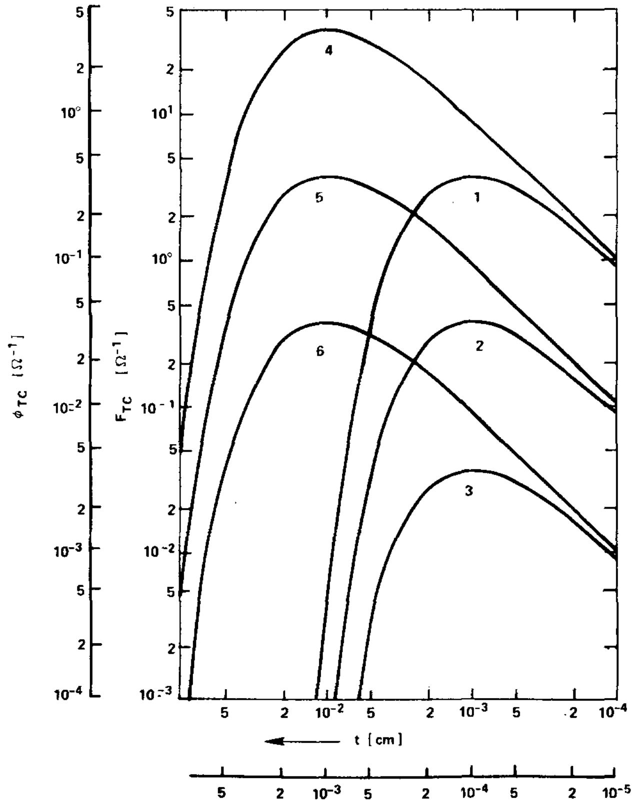

FIG. 1. Figure of merits F_{TC} and ϕ_{TC} as function of film thickness: curve 1: $\alpha = 10^3$ cm^{-1}, $\sigma = 10^4\ \Omega^{-1}$ cm^{-1}; curve 2: $\alpha = 10^3$, $\sigma = 10^3$; curve 3: $\alpha = 10^3$, $\sigma = 10^2$; curve 4: $\alpha = 10^2$, $\sigma = 10^4$; curve 5: $\alpha = 10^2$, $\sigma = 10^3$; curve 6: $\alpha = 10^2$, $\sigma = 10^2$.

An illustration of the values which ϕ_{TC} can assume in practical transparent conductors is given in Table I. Five coatings were evaluated. Their optical transmissions versus wavelength were measured with a recording spectrophotometer and their electrical sheet resistances determined with a four-point probe. Table I also lists literature data for sputter-coated In_2O_3/SnO_2. For comparison, F_{TC} has been calculated and included in the table.

Table I clearly shows the expected characteristics of ϕ_{TC} and F_{TC}. Since ϕ_{TC} places less weight onto R_s, coatings with higher transmissions have larger ϕ_{TC} values. This difference between ϕ_{TC} and F_{TC} is best seen by comparing NESA and BALTRACON. Although

TABLE I. Comparison of figure-of-merit values F_{TC} and ϕ_{TC} for transparent conductor films.

Material	T [a]	T^{10}	R_s (Ω/square)	F_{TC} ($10^{-3}\ \Omega^{-1}$)	ϕ_{TC} ($10^{-3}\ \Omega^{-1}$)
NESA [b]	0.80	0.11	120	6.7	0.9
NESATRON [c]	0.82	0.14	20	41	7.0
BALTRACON [d]	0.87	0.25	200	4.3	1.2
SnO_2 [e]	0.85	0.20	10	85	20
In_2O_3/SnO_2 [f]	0.83	0.16	3.1	270	52
Cd_2SnO_4 [g]	0.84	0.17	2.4	350	71

[a] Average transmission at 5500 Å, substrate absorption included.
[b] Commercial SnO_2-coated glass (PPG).
[c] Commercial In_2O_3-coated glass (PPG).
[d] Commercial In_2O_3-coated glass (Balzers).
[e] Spray-coated SnO_2 from Photon Power, Inc.
[f] Sputter-coated data from Ref. 1.
[g] Sputter-coated; preparation see Ref. 4.

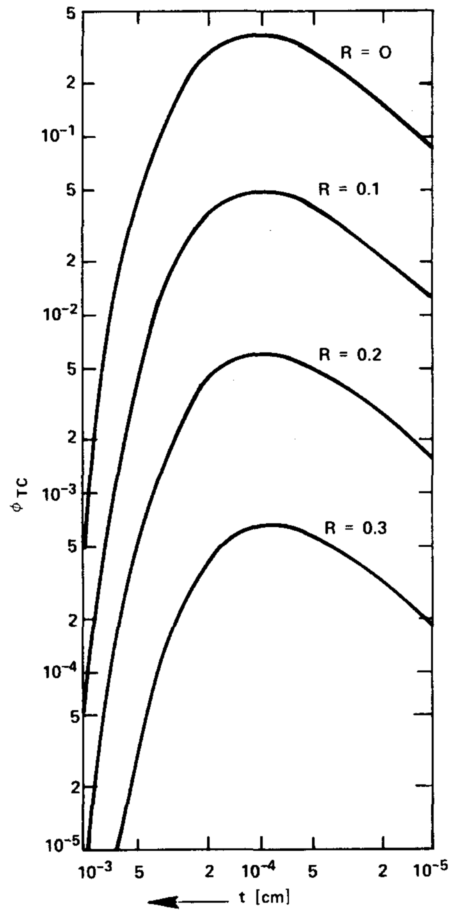

FIG. 2. Figure of merit ϕ_{TC} vs film thickness with reflectivity as parameter; $\alpha = 10^3$, $\sigma = 10^4$.

the particular NESA sample of Table I appears to be a better transparent electrode when judged by F_{TC}, the reverse is true when ϕ_{TC} is used for evaluation. The higher transmission of the BALTRACON sample gives it a larger ϕ_{TC} over NESA and this theoretical superiority is confirmed in practical applications. For instance, in display devices, when a low R_s is not required, a higher transmission of the front electrode improves the visual appearance. Naturally, a large transmission coupled with a very low sheet resistance results in the highest ϕ_{TC} values as can be seen for the case of Cd_2SnO_4.

The second-half of Eq. (6) is strictly valid only when reflection losses from the transparent conductor surface can be neglected. If this is not the case, Eq. (2) has to be replaced by[2]

$$T = (1-R)^2[\exp(\alpha t) - R^2 \exp(-\alpha t)]^{-1}, \qquad (7)$$

where R is the reflectivity. With Eq. (7) we obtain for the figure of merit

$$\phi_{TC} = \sigma t\{(1-R^2)[\exp(\alpha t) - R^2 \exp(-\alpha t)]^{-1}\}^{10}. \qquad (8)$$

The above expression reverts to Eq. (6) when $R = 0$.

Inclusion of the reflectivity in the figure of merit reduces the ϕ_{TC} values. Examples are shown in Fig. 2 in which ϕ_{TC} is plotted as a function of film thickness with $\alpha = 10^3$ cm^{-1}, $\sigma = 10^4$ Ω^{-1} cm^{-1}, and R as parameter. The curve for $R = 0$ is identical to curve 1 in Fig. 1.

The evaluation of transparent electrodes for practical applications requires that the optical transmission and R_s are measured. The figure of merit can then be calculated from T^{10}/R_s. Since standard transmission measurements include reflection losses the foregoing procedure yields a valid ϕ_{TC} and Eq. (8) is not needed. This equation, however, should be used if the transparent electrode properties of a particular material are to be predicted from its fundamental material parameters, α, σ, and index of refraction n.

CONCLUSIONS

The figure of merit ϕ_{TC} provides a useful tool for comparing the performance of transparent conductive coatings when their electrical sheet resistance and optical transmission are known. Furthermore, the expressions derived for ϕ_{TC} can be used to predict the transparent electrode properties of a candidate material from its fundamental parameters. To illustrate this latter point we have calculated ϕ_{TC} for three metal films (Cu, Ag, and Au) and compared them to the best known transparent semiconductor oxides Cd_2SnO_4 and In_2O_3/SnO_2 (ITO). The results of these calculations are plotted in Fig. 3.

The curves of Fig. 3 were obtained by using Eq. (6) instead of Eq. (8). This simplification is justified because the reflectivities of the metal films decrease with film thickness in the range of interest[3] and become similar to those of the two semiconductors at the selected wavelength (5500 Å). Since the main purpose of this analysis is a general comparison of metal and semiconductor transparent electrodes, neglect of R does not alter the conclusions below.

The curves for the two semiconductors were calculated with $\alpha = 10^3$ cm^{-1} for both materials and $\sigma = 6.5 \times 10^3$ Ω^{-1} cm^{-1} for Cd_2SnO_4 [4] and $\sigma = 5.6 \times 10^3$ Ω^{-1} cm^{-1} for ITO.[1] Bulk values of α [5] and σ [6] were taken for the

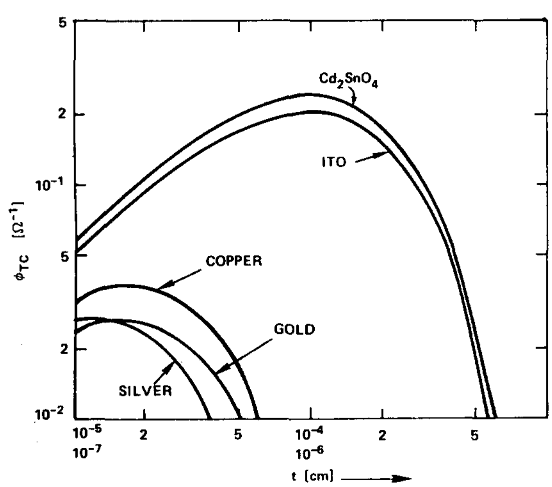

FIG. 3. Calculated ϕ_{TC} vs film thickness for metal and semiconductor films at 5500-Å wavelength; upper abscissa for Cd_2SnO_4 and ITO, lower abscissa for Cu, Ag, and Au.

metals so that their calculated figure of merits represent upper limits.

Figure 3 illustrates that semiconductors are superior transparent electrode materials when compared to thin metal films. The differences in ϕ_{TC} become even more pronounced when we take into consideration that the maximum ϕ_{TC} for the metals occurs between 10- and 20-Å film thickness. In this thickness range metal films are not yet continuous and, therefore, have much larger sheet resistances than would be expected from the bulk conductivities. Hence, the calculated maximum ϕ_{TC} cannot be achieved in single-layer metal films.

Although the preceding analysis shows that metal films can hardly compete as transparent electrodes with semiconductor oxides on a figure of merit basis they are still useful for practical applications. Especially thin gold films can be of considerable value when maximum ϕ_{TC} is of less importance than requirements such as easy and fast deposition, cold substrates, or chemical compatibility.

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