EMI SHIELDING WITH TRANSPARENT EC COATINGS

Introduction

Optical coatings which are transparent yet electrically conductive (EC) are finding increased use in numerous applications. Most engineers or optical designers are familiar with the characteristics, performance and typical specifications for optical coatings used, for example, to provide antireflection of glass. However, when these people must specify a transparent EC coating for a given application the result is usually a specification which is either incorrect, or at least, far from optimum for that application. The purpose of this article is to provide the information and insight needed to correctly specify and select a transparent conductive coating for your EMI shielding application.

EC Coating Fundamentals

Transparent conductive coatings can be divided into two general categories: semiconductive metal oxides and conductive thin metal films. The most common representatives of these two categories are Tin Oxide or Indium Tin Oxide (ITO) and Gold. Some of the differences and similarities between these two classes of EC coatings will be described with emphasis on their characteristics as Video Display Terminal (VDT) EMI Shields. First, however, a review of some pertinent fundamentals and nomenclatures is required.

Electrical Characteristics. The conductivity, σ, of a coating is usually described by the inverse characteristic, resistivity. Conductive thin films are typically characterized in terms of surface resistivity (sheet resistance), R_s, in "ohms per square" rather than volume resistivity, ρ, in ohm-centimeters. The surface resistivity for a rectangular area is derived from Ohm's law of resistance, R, by including the thickness, t, with the volume resistivity, ρ, to define a new parameter, R_s, the surface resistivity, i.e.,

$$R = \frac{\rho\, 1}{t \cdot w} = \frac{R_s 1}{w} \text{ where } R_s = \frac{\rho}{t} = \frac{1}{\sigma t} \tag{1}$$

The total resistance of a rectangular coated area is equal to the resistivity of the coating multiplied by the ratio of the separation between bus bars, 1, divided by the width of the bus bars, w. Thus, when the coated area is square, the length, 1, between parallel bus bars, equals the width, w, and the two cancel with the result that the total resistance, R, equals the surface resistivity, R_s, in ohms. Hence, the term "ohms per square."

Note that in general the resistance measured at the terminals (ohms), i.e., between bus bars, is not equal to the coating surface resistivity (ohms/square). Recall also that ρ is an inherent property for a given pure bulk material but that R_s is dependent on the coating thickness as well. Thus, for metallic EC coatings of a given material, variation in the R_s value is achieved only by changing the deposited thickness, while for semiconducting EC coatings, ρ can be altered by doping so that a different coating R_s value may be caused by either thickness or doping changes.

Optical Characteristics. The important transmission characteristics of an EC film for a given application are the spectrally weighted values pertinent to that application, i.e., the spectral matching factor value, and not necessarily those which give the maximum average transmission over some wavelength interval. For traditional applications involving a human observer or operator, the eye-sensitivity weighted (luminous) visible transmittance value is the appropriate performance criterion. Luminous transmittance, LT, is defined as follows:

$$LT = \frac{\int S(\lambda)K(\lambda)T_{EC}(\lambda)d\lambda}{\int S(\lambda)K(\lambda)d\lambda} \cong \frac{\Sigma_{\lambda_1}^{\lambda_2} S(\lambda)K(\lambda)T_{EC}(\lambda)\,\Delta\lambda}{\Sigma_{\lambda_1}^{\lambda_2} S(\lambda)K(\lambda)\Delta\lambda} \tag{2}$$

Where $S(\lambda)$ is the spectral distribution of the light source, $K(\lambda)$ is the visibility factor for the photopic adapted eye and $T_{EC}(\lambda)$ is the spectral transmittance of the electrically conductive coating.

A typical example is the viewing of a Liquid Crystal Display (LCD) through an EC coated window EMI shield with ambient lighting from (white) flourescent lamps or sunlight. These light sources are essentially neutral over the visible waveband so that $S(\lambda) \cong 1$ in Equation (2). Consider now an EC coating with the spectral transmittance, $T_{EC}(\lambda)$, values listed in column 2 of Table 1. Also listed are the relative eye-sensitivity, $K(\lambda)$, values (column 3) and the product of these two parameters, $T_{EC}(\lambda)K(\lambda)$, (column 4).

The average transmittance, T_{AVE}, is simply the sum of the spectral values divided by the number of sampling values, N. For this example, from Table 1;

$$T_{AVE} = \frac{\Sigma\, T_{EC(\lambda)}}{N} = \frac{5.65}{7} = .807 \text{ or } T_{AVE}\% = 80.7\%. \tag{3}$$

Now the luminous transmittance value is calculated from Table 1 as follows:

$$LT = \frac{\Sigma\, K(\lambda) \cdot T_{EC}(\lambda)}{\Sigma\, K(\lambda)} = \frac{1.79506}{2.0985} = .855 \text{ or } LT\ \% = 85.5\% \tag{4}$$

Thus, this EC coating exhibits about 5% more luminous transmittance than average transmittance. This can be easily understood by noting in Table 1 (column 3) that only wavelengths near the peak "detector" (eye) sensitivity at 550 nm have significant response and hence improving the EC coating transmittance at other wavelengths is of very little usefulness. Furthermore, if the coating design were adjusted to enhance the extremes of the visible waveband the central wavelengths would have reduced transmittance causing the LT value to drop. Thus, average transmittance should not be specified in application involving (only) the human eye; luminous transmittance should be specified.

The optical characteristics of EC coatings are not independent of their electrical properties. The transparency of conductive thin films is fundamentally limited by their absorbtivity, mainly by charge carriers. Reflective losses can be greatly reduced or eliminated by optical interference techniques, e.g., thickness control or antireflection coatings. Figure 1 presents typical corresponding values of luminous external transmittance, i.e. the transmittance a coated part actually measures including substrate (all) losses, versus surface resistivity for a metallic EC coating

λ	$T_{EC}(\lambda)$	$K(\lambda)$	$T_{EC}(\lambda)K(\lambda)$
400 nm	.70	.0004	.00028
450 nm	.75	.0380	.02850
500 nm	.80	.3230	.25840
550 nm	.85	.9950	.84575
600 nm	.90	.6310	.56790
650 nm	.85	.1070	.09095
700 nm	.80	.0041	.00328
	$\Sigma T_{EC}(\lambda) = 5.65$	$\Sigma K(\lambda) = 2.0985$	$\Sigma T_{EC}(\lambda)K(\lambda) = 1.79506$

Table 1. Comparison of EC Coating Transmittance and Human Eye Sensitivity.

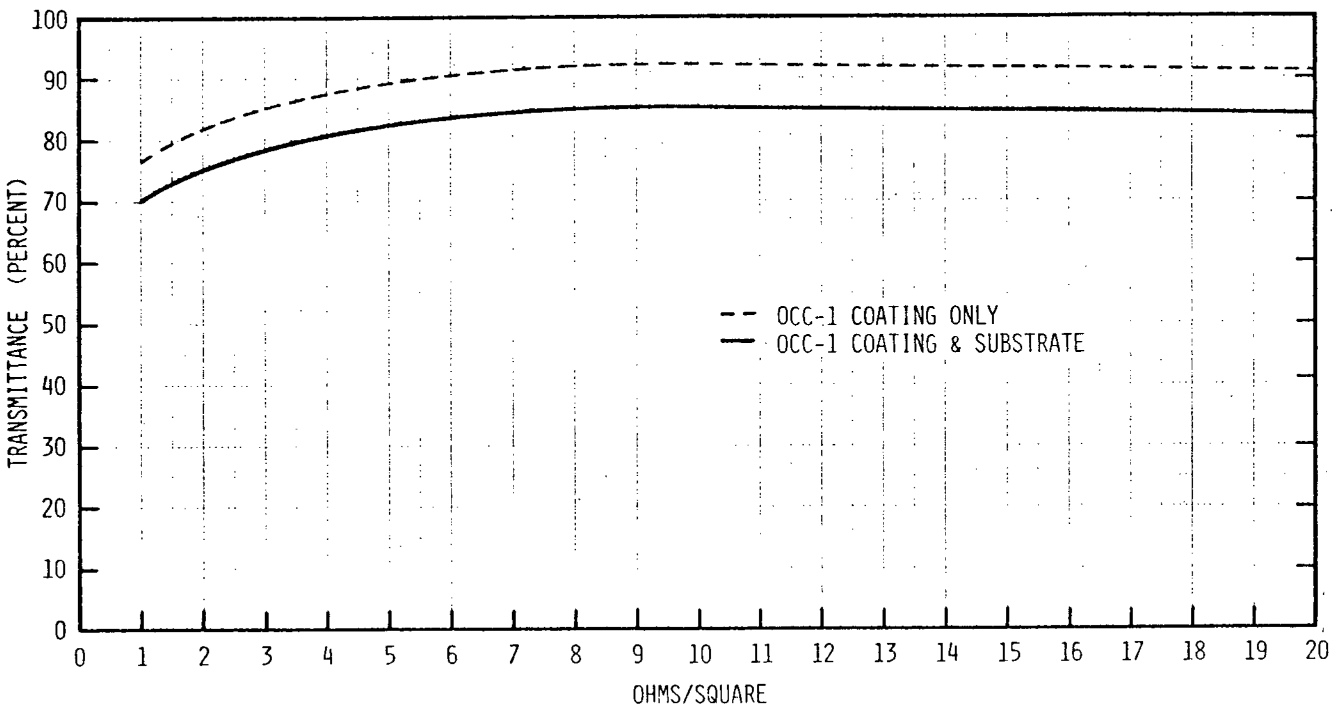

Figure 1. OCC-1 Luminous Transmittance vs. Surface Resistivity.

(Ref. 1). Some EC coating manufacturers give coating only "transmission" values (which ignore substrate losses), so for comparison that data is also given in Figure 1 as a dotted curve. However, great care must be used in applying these somewhat artificial coating only "transmission" values to conditions other than those used in the original measurement. Note the $T_{EC}(\lambda)$ values used in the previous example were the applicable external spectral transmittance values.

Thus, the light transmittance value achieved with an EC coating is a function of resistivity and a compromise between the desired (ideal) electrical and optical properties must be made. Optical properties of the EC coatings other than transmittance may be important in some applications. For example, the eye-weight (luminous) reflectance from an EC coating should be low when used in viewing or display application.

EMI Shielding Performance

The capability of electronic devices and systems to operate without mutual interference is called Electromagnetic Compatibility (EMC). Both commercial (FCC) and military EMC regulations specify maximum acceptable levels of EMI in specific frequency ranges for various application categories of electronic equipment. If these levels of electromagnetic radiation are exceeded, the radiating device is considered a noise source and will require some form of EMI shielding to meet these regulations. In addition certain applications which involve the display of sensitive data, for example in banking or classified military use, may require additional shielding to prevent unauthorized knowledge of this data through detection of the EM radiation from the display.

Transparent EC coatings on the display or cover window are very effective attenuators of the electromagnetic radiation. The Shielding Effectiveness (SE) of an EC coating may be expressed as follows:

$$SE = A + R + B \text{ in dB}$$

where A is the attenuation by absorption, R is the attenuation by first surface reflection and B is the additional attenuation due to multiple internal reflections.

The distance, r, from the source of EM radiation to be attenuated to the transparent EC coating is critical in determining the SE achieved. In fact, the critical parameter is actually the ratio of this distance to the wavelenght, λ, of the interfering radiation. Considerable simplification results in the appropriate formulae when approximations can be introduced and two regions are defined as follows:

Near field region $\quad r < \lambda/2\pi$

Far field region $\quad r > \lambda/2\pi$

In the far field region the SE is independent of the distance, r, and of the frequency of the EM wave; thus, only knowledge of the transparent EC coating surface resistivity (ohms/square) is required to calculate the attenuation achieved (Ref. 2). However, many applications, such as shielding for Video Display Terminals (VDT) are in the near field region and therefore the SE calculation is more complicated. As an example, we will calculate the SE achieved at a frequency of 300 MHz with an ITO and a Gold EC coating, each of 20 ohms/square surface resistivity located 1.0 inches from the interfering source.

A typical ITO EC coating has a volume resistivity, ρ, of about 4×10^{-4} Ω-cm and a thickness, t, of about 2×10^{-5} cm for an EC film of about 20 ohms/square. The absorption contribution to the SE is given by:

$$A_{ITO} = 8.686\,(\alpha\, t) \tag{5}$$

where the absorption coefficient $\alpha = \sqrt{\pi f \mu \sigma} = 1.72 \times 10^2$ cm^{-1}. Thus, $A_{ITO} = 2.59 \times 10^{-2}$ dB.

A typical 20 ohms/square Gold thin film has a (effective) volume resistivity, ρ, of $1 \cdot 10^{-5}$ Ω-cm and a thickness, t, of $5 \cdot 10^{-7}$ cm. The absorption coefficient at 300 MHz is $1.09 \cdot 10^3$ cm^{-1} and hence the $A_{Gold} = 4.73 \times 10^{-3}$ dB. Therefore, the A value for both EC coating types is nil!

Next we calculate the total E-field Reflection (R + B) for the ITO coating as follows:

$$R + B = 20 \log_{10} \frac{k\,t}{r f \rho} \tag{6}$$

Where k is a constant, r is the source to shield distance, f is the frequency and ρ, t are given above. The result for this example with r = 1.0″ is 35.4 dB. Thus, the total $SE_{ITO} = A + R + B$, for the ITO film is 35.4 dB.

A similar calculation using Eq. (6) for the Gold coating using the appropriate parameter values presented above gives a total SE_{Gold} = 35.4 dB. Thus, the same SE is calculated for ITO and for Gold EC coatings of the same surface resistivity (ohms/square).

This example demonstrates two important conclusions:

1. For transparent EC coatings absorption is virtually zero and attenuation is achieved only by reflection; thus, only terms R and B are used.
2. The SE of a transparent EC coating (with $t \ll 1/\alpha$) is dependent on the ohms/square only, and not on the type of EC coating.

Note, however, that these conclusions are not valid for thick nontransparent conductive coatings.

Consider the following example of a typical VDT with a CRT display and required to meet the FCC class "B" requirements. The frequency range of this requirement is from 30 MHz to 1 GHz which can be conveniently divided in bands of 30 to 100 MHz, 100 to 300 MHz and 300 MHz to 1 GHz. In these bands the required SE for E-fields is about 55 dB, 45 dB, and 15 dB, respectively, (Ref. 3).

Assume that the VDT in this example is in a metal box so that only the CRT is a leakage opening and that the EMI sources are located within the unit, rather than in neighboring equipment, and at near field distances from this opening. If a transparent ITO EC coating of 100 ohms/square were used to cover the CRT aperture (and properly grounded) would the SE be sufficient to meet these required attenuation levels? Calculations of the SE using Eq. (6) gives the results in Table 2. These values are below or near the required SE values in the various bands; thus, a lower resistivity coating is needed. Generally, the SE value should exceed the required attenuation by ≥ 6 dB for a minimum signal/noise safety factor of 2. For this example, an EC coating on about 20 ohms/square is needed to increase the SE value by 14 dB.

f =	30-100 MHz	100-300 MHz	300-1000 MHz
SE needed FCC Class B	55 dB	35 dB	15 dB
SE 100 Ohms/Square EC Coating	42.2 dB	32.2 dB	22.2 dB
SE 20 Ohms/Square EC Coating	56.2 dB	46.2 dB	36.2 dB

Table 2. SE for 100 ohms/square and 20 ohms/square. EC Coatings vs. FCC Requirements.

f =	3-10 MHz	10-30 MHz	30-100 MHz	100-300 MHz	300-1000 MHz
SE needed MIL-STD-461A	75 dB	75 dB	65 dB	45 dB	25 dB
SE 5 Ohms/Square EC Coating	88.2 dB	78.2 dB	68.2 dB	58.2 dB	48.2 dB

Table 3. SE for 5 ohms/square. EC Coating Versus MIL-STD-461A Requirements.

As a second example, consider a CRT display system with the same operating parameters but requiring protection to meet the more stringent MIL-STD-461A. The approximate attenuation required in various frequency bands (Ref. 3) is given in Table 3.

Comparing these values with those for the VDT with a 20 ohms/square EC coating meeting the FCC requirements indicates that about 10 dB of additional shielding is needed in those same frequency bands. Shielding is also required in lower bands. Since each factor of 2 reductions in the ohms/square of the EC coating provides an additional 6 dB attenuation, we can estimate that a resistivity of about 5 ohms/square will be required.

Calculated values of the SE in the various frequency bands for a 5 ohms/square resistivity coating are listed in row 2 of Table 3. Thus, a 5 ohms/square transparent EC coating can provide adequate attenuation but what are the obtainable optical properties? A plot of resistivity versus luminous transmittance for metallic EC coatings from one manufacturer (Ref. 1) is shown in Figure 1. A LT value of 82% corresponds to a 5 ohms/square coating resistivity.

Thin film EC coatings can provide even greater SE and maintain good transparency. From Figure 1 again, an EC coating resistivity of about 1 ohm/square can still achieve 70% LT. The calculated SE from Eq. (6) for a 1 ohm/square EC coating at, for example, 10 MHz is 97 dB.

Conclusions

It has been shown that transparent EC coatings can be effective EMI/RFI shields and can provide enough attenuation for a typical VDT to meet both FCC and Military Specifications. Transparent EC coatings achieve Shielding Effectiveness, SE, (attenuation) by reflection, not absorption which, however, is important in opaque thick films. The SE value, with fixed test conditions, is dependent only on the surface resistivity, (ohms/square) of the EC coating, not on the coating type.

The different SE values which are given in articles or by various EC coating manufacturers are caused, excluding errors, by different measurement conditions or by different assumptions and approximations in calculated values. The distance between the EC coating shield and the interfering source is a critical parameter in determining the SE value achieved at various frequencies. If this distance is not the same in two measurements or calculations then corrections must be made to allow data comparison.

Either metal oxide or metallic EC coatings of equal resistivity can be used interchangeably to achieve a given level of attenuation; however, the corresponding optical transparency will, in general, not be equal for the two coating types. The SE is an inverse logarithmic function of coating resistivity; increased attenuation is achieved with lower resistivity coatings and reduced shielding with higher resistivity films. The percent transmittance achieved with either coating type is also an inverse function of the coating resistivity.

For applications involving human vision, the pertinent optical parameter is luminous transmittance, not average visible transmittance. "Transmission" values, which ignore substrate losses should be avoided; these artificial EC coating only data can easily be misleading or misapplied in real applications. Therefore, when selecting transparent EC coating for your shielding application, request manufacturers' data which present the tradeoff between luminous transmittance and coating resistivity. This information along with SE data, including the test conditions, will allow selecting an optimal EC coating for your requirements.

References

1. Optical & Conductive Coatings, 428 N. Buchanan Circle, No. 8, Pacheco, California, 94553
2. White, Donald R. J., A Handbook on Electromagnetic Shielding Materials and Performance, Don White Consultants, Gainsville, Virginia, 22065
3. Kendall, Chris M., Chris Kendall Consultants, Running Springs, California, 92382

This article was written for ITEM by Clark Bright, Technical Director, Optical Conductive Coatings, Pacheco, CA.