Optical Method for Sheet Resistance Measurement of Transparent Thin Films

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ABSTRACT

The sheet resistance of transparent conductive layers is an important quantity in many production processes. Examples are top electrodes for inorganic and organic photovoltaic devices or windscreens for vehicles. The films are applied either on individual substrates as in the case of windscreens or on thin glass or foils in a roll-to-roll process. A measurement solution for determining the film's sheet resistance should be fast, non-contact and non-destructive. Therefore optical transmittance and/or reflectance measurements in the visible to near infrared wavelength range are an ideal solution that is easy to integrate. It is possible to get one or more spectra of each product during the manufacturing process. The connection between the optical spectrum and the sheet resistance or conductivity is made by a physical model. Today computer are quick enough that an analysis module based on the model can be implemented, that is fast enough for in-line, real time quality control. The application of this method to different materials and its relation to other measurement methods is discussed.

INTRODUCTION

Transparent conducting thin films find a wide field of applications. Examples are top electrodes for displays, solar panels or windscreens in the automotive industry. They are produced on large scale production sites and in high volumes, so that a simple, robust and effective measurement method, capable of measuring each produced unit nondestructively, is important for quality control. Among the classical methods of measuring sheet resistance or conductivity are 4-point probe and eddy-current measurements. 4-point probe measurements - while being simple - require the probe to contact the sample and thus are not usable for process control in many applications. Another constraint is the fact that they cannot measure layers that have one or more insulating layers on top of them. Eddy-current measurements do not come in contact with the sample and can measure "buried" layers, but they are susceptible to distance variations between the probe and the sample. Optical spectra - especially transmittance - can be realized in a way that is independent from changes in sample - probe distance. This is an important factor when implementing a measurement method on a vibrating web or on curved surfaces.

Typically the measurement systems used to obtain optical spectra utilize either a halogen or a xenon bulb as the light source and one or more photo spectrometers as detectors. Such systems can cover a wavelength range from the near ultraviolet to the near infrared region. As an example, a system could cover 400 nm to 1700 nm when using a halogen light source and CCD and InGaAs detectors in the photo spectrometers. FTIR spectrometers have a typical wavelength range from 1 to 10 µm, but they miss the visible range and are not very easily adapted to process environments.

CALCULATING SHEET RESISTANCE

To determine the sheet resistance or conductivity out of the measured spectra, the data have to be fitted to a physical model. The model treats the sample as a stack of different layers. Each layer is defined by its thickness, refractive index n and absorption coefficient k. The last two quantities are typically dependent on wavelength. They can be supplied to the model either as fixed data set or by defining a dispersion model. Dispersion models describe the dielectric constant or complex refractive index as a function of wavelength or frequency and other parameters. They can be empirical or semi-empirical as in the form of the well-known Cauchy model [3]. A dispersion model, that is valid over a larger wavelength range, will contain different contributions. Because of the superposition principle for electromagnetic fields, models are obtained by adding different contributions, that are necessary for a given material.

To describe the contribution of free carriers in a material to the dielectric function, and therefore transmittance and reflectance, a Drude model (eq 1) proves to be very efficient.

$$\varepsilon_{Drude}(\omega) = 1 - \frac{\Omega_P^2}{\omega^2 + i\omega\Omega_R} \qquad (1)$$

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ϖ is the frequency of the light wave, Ω_p is the plasma frequency and Ω_R is a damping constant. The inverse of the damping constant is the time a carrier can travel freely in the material under the influence of an electric field, before it is scattered. By putting this susceptibility into the Maxwell equation, the conductivity can be calculated as:

$$\sigma_0 = \Omega_P^2 \cdot \varepsilon_0 \cdot \frac{2\pi}{\Omega_R} \tag{2}$$

The resistivity is just the inverse of the conductivity (eq 3). Sheet resistance is calculated by dividing the resistivity by the layer thickness (eq 4).

$$\rho_0 = \sigma_0^{-1} \tag{3}$$

$$R_{sheet} = \frac{\rho_0}{d} \tag{4}$$

The unit of the sheet resistance is ohm, but it is common to denote it as Ω/❑.

With some materials, it can be necessary to use an extended Drude model in which the damping is not constant but depends on frequency. The scattering of carriers by charged impurities in a semiconducting material is an example. In the extended model Ω_R is split into two numbers $\Omega_{R,low}$ and $\Omega_{R,high}$ for the low and high frequency range and the calculation in eq. 4 is done by using $\Omega_{R,low.}$

APPLICATIONS

Focusing on the wavelength range from 200 nm to 2000 nm, there are various types of materials that can be fitted. Metals become transparent in the ultraviolet region. Silver, which becomes transparent below 300-350 nm has a resistivity of approximately 1.59 x 10^{-8} Ω. If we fit a model as described to the reflectance data of a 100 nm thick silver layer (n and k data taken from [4]), we obtain 74349 cm^{-1} for Ω_p and 142.6 cm^{-1} for $\Omega_{R.}$ This yields a value for the sheet resistance of 0.155 Ω/❑ in comparison to 0.159 Ω/❑, if we divide the literature value by the 100 nm layer thickness.

An important group of materials are transparent conductive oxides (TCO). Zinc-oxide (ZnO), aluminum-zinc-oxide (AZO) and indium-tin-oxide (ITO) are prominent members of this group and widely used in displays and solar panels. Their plasma frequencies are in the near infrared, just above the visible spectrum, so that they combine transparency in the visible range with electrical conductivity. For TCO on glass, the analysis of optical spectra to obtain sheet resistance has the advantage of getting film thickness and transparency in one measurement. Often film thickness is in the range from 100 nm to a few microns. Because a change will not only influence the resistance but also the optical transmittance, it can result in unwanted color cast and has to be controlled precisely.

Figure 1 shows a spectrum of an intrinsic ZnO/AZO stack on glass. The glass substrate is too thick to show oscillations in the spectrum, so that the fringes in the 400 - 1000 nm range come from the two TCO layers. Both layers have to be described by extended Drude models. To fit the fringes, one has to take into account further contributions to the dielectric function. In this case the model was constructed using:

- a constant dielectric background
- an OJL [5] model for an interband transition
- the extended Drude model

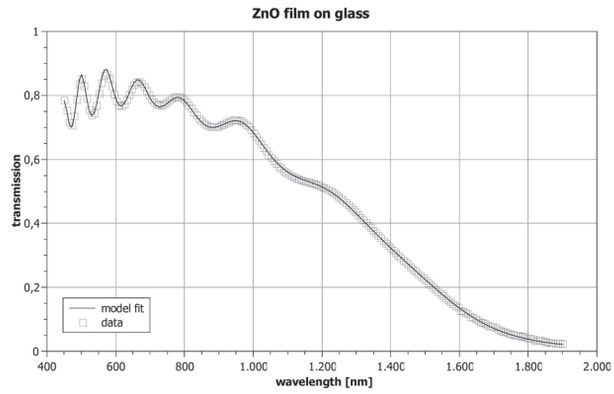

Figure 1: Transmittance spectrum of an AZO layer on top of a ZnO layer on a glass substrate. The solid line is the fit to the optical data.

This model was used for the i-ZnO and the AZO material. The thicknesses of the stack was (from top to bottom):

- AZO 736 nm
- iZnO 194 nm
- glass 3 mm

The glass thickness was measured by conventional means using a caliper and dialed into the parameter set as a fixed value. It has to be noted, that it is necessary to measure and analyze a set of different samples including the glass substrate alone as well as an iZnO/glass and an AZO/glass stack, before it is possible to come up with reasonable numbers for all the parameter for all the parameters.

The fit shows good agreement with the measured spectrum and yields a sheet resistance of 10 Ω. It is important to note, that both layers contribute to the conductivity, as there is no insulating layer in between them. In this case, the layers can be treated as if they both represent resistors connected in parallel.

Another example is shown in Figure 2. Here the layer stack is composed of an organic conducting material, PEDOT:PSS (poly(3,4-ethylenedioxythiophene) polystyrene sulfonate) on top of a non-specified handling layer on a PET (poly-

ethylenterephthalat) foil. In the given range, the model for PEDOT:PSS is build up from the following contributions:

- a constant dielectric background
- a Kim oscillator model [5]
- the extended Drude model

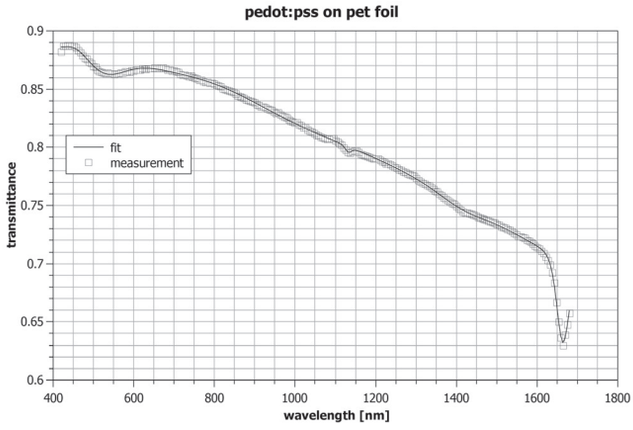

Figure 2: Transmittance measurement and model fit of an PEDOT:PSS layer on a PET foil.

The handling layer is a simple dielectric with a dispersion relation that is described by:

- a constant dielectric background
- a Kim oscillator model [5]

Again fitting was done on set of samples with different thicknesses and containing the PET foil without coating and handling layer / PET samples.

The analysis yields a sheet resistance of 333 Ω/❑ and a layer thickness of 110 nm. The foil thickness was kept constant at 0.127 mm.

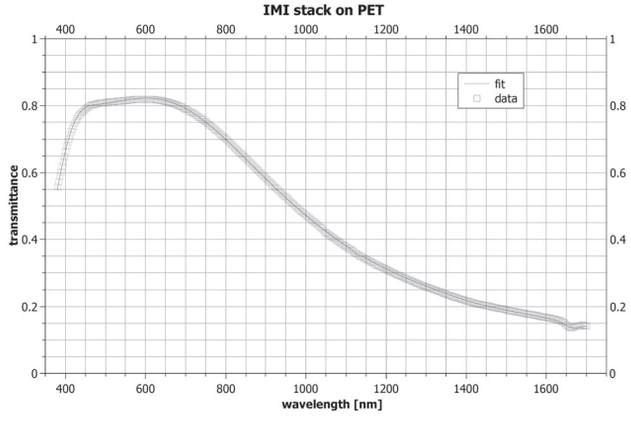

Figure 3: Transmittance and model fit of an IMI stack on a PET foil.

The last example shows an ITO-metal-ITO (IMI) stack on top of a PET foil. Thickness of the foil is 150 nm. The metal layer is silver. IMI stacks can reach high optical transmittance and have a higher conductivity compared to a single ITO layer. Again the ITO layer is modeled with:

- a constant dielectric background
- an OJL [5] model for an interband transition
- the extended Drude model

whereas the silver layer is fitted with a model that uses a constant dielectric background and a Drude model. Because the silver layer is only a few nm thick, the material parameters are different from the bulk parameters mentioned at the beginning and need to be recalculated. The thicknesses in the example above come from the calculation as

- 35 nm for the top ITO layer
- 15 nm for the silver layer
- 25 nm for the bottom ITO layer

The calculated sheet resistance is 16 Ω/❑.

CORRELATION WITH OTHER METHODS

The Drude model is about the movement of free carriers. A conducting material is described as a lattice of ions in which the free carriers form a kind of gas. If an electric field E is applied, the carriers of charge q are accelerated by a force $F = q \cdot E$. This acceleration would continue as long as the field E is applied. If this would be the case, the current would not be constant and Ohm's law would be invalid. The explanation given in Drude's model is, that the carriers interact with the lattice and reach an equilibrium after a short time. The model uses a collision time to account for this in the equation of motion. Solving the equation of motion with this assumption yields eq 1, which we used here for modeling the contribution of the conductivity to the optical characteristics of the material.

Looking at the various measurement methods, 4-point probe, eddy current and transmittance/reflectance measurements it becomes clear, that they differ mainly in the way the force is applied on the carriers. A 4-point probe applies a dc voltage and thus a force that is constant over time whereas eddy current and light apply ac signals, however in very different frequency ranges. Because the collision time is very short and comparable with optical frequencies, a carrier in an ideal solid-state material will not "feel" a large difference depending on the method being used. In reality however there are factors that can result in differences between the methods. If the surface is rough the layer will start to scatter light and the transmittance will drop. If this scattering cannot be accounted for correctly in the optical model, its prediction will be off. The dependency on thickness however will not

change and optically retrieved values can still be matched to other measurements by a simple linear scaling. Especially in process control applications, it is often sufficient to monitor the variations around a given set point and using the optical method remains a useful choice even if the data have to be scaled to agree with other data.

It has to be pointed out, that 4-point probe measurements and eddy current methods also are constrained and may not provide correct values, when the measurement conditions are unfavorable. For instance, for thin foils the contact of the 4-point probe can become a problem and both methods will fail on micro-structured samples when there is no electrical conductivity over distances that are large enough for the probe heads.

CONCLUSION

Fitting optical dispersion models based on the Drude equation to transmittance and or reflectance measurements is a useful method in determining the conductivity and sheet resistance of thin conducting films used for optoelectronic applications. Measurements in the 400 - 2000 nm range can be used for a variety of different materials in including metals, metal-oxides and organic conducting materials. The method has the advantage that it is fast, non-contact and non- destructive. Furthermore this measurement also simultaneously provides film thicknesses which are generally used for production and quality control. Even though it is not always possible to adjust the model to give absolute numbers, the data from the models can be used to implement an efficient and easy to integrate on-line process control solution.

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REFERENCES

1. Paul Drude, “Zur Elektronentheorie der Metalle”, Annalen der Physik. 306, Nr. 3 (1900) 566–613. http://dx.doi.org/10.1002/andp.19003060312

2.Paul Drude, “Zur Ionentheorie der Metalle”, Physikalische Zeitschrift. 1 (1900) 161–165.

3. F.A. Jenkins and H.E. White, Fundamentals of Optics, 4th ed., McGraw-Hill, Inc., 1981.

4. P.B. Johnson and R.W. Christy, “Optical Constants of the Noble Metals”, Phys. Rev. B. 6, 12, (1972) 4370 - 4379. http://dx.doi.org/10.1103/PhysRevB.6.4370

5. S.K. O'Leary, S.R. Johnson, P.K. Lim, J. Appl. Phys. Vol. 82, No. 7 (1997), 3334-3340. http://dx.doi.org/10.1063/1.365643

6. C.C. Kim, J.W. Garland, H. Abad, P.M. Raccah, Phys. Rev. B 45 (20) (1992) 11749-11767. http://dx.doi.org/10.1103/PhysRevB.45.11749