Int. J. Nanoelectronics and Materials **6** (2013) 87-95

Electric field distribution in weakly absorbing monolayer at oblique incidence of light

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Received 1 March 2012; Revised 24 June 2012; Accepted 3 July 2012

Abstract

Calculation of the electric field intensity of light incident obliquely on a single layer of SnO_2 thin-film coating of weakly absorbing material is presented. The analysis utilizes matrix formulas based on Abele's formulas from the calculation of reflectance and transmittance. Partial absorption due to a certain depth in the prepared film by using chemical spray pyrolysis technique was also investigated. The present study offers a useful tool in the understanding of the mechanism of light absorption in many applications, and it is convenient to use where intensity of the visible and near infrared spectrum are of interest.

Keywords: Electric field intensity, Matrix formulas, Reflection spectroscopy, Spray pyrolysis technique.
PACS: 83.60.Np, 02.10.Yn, 78.40.-q, 81.15.Rs.

1. Introduction

Transparent conducting oxides SnO_2 have attracted much attention due to their optical and electrical properties in comparison with other metal oxides [1,2]. It is well known that at optical frequencies, it is the electric field intensity of the light that is responsible for many interactions with materials. The understanding of distribution of electric field in an optical coating material may lead immediately to an understanding of many important effects including absorption, scattering, and contamination sensitivity [3-7].

For a multilayer system, the profile of the electric field system has played an important role in the analysis of various kinds of spectroscopy, such as spatially reflection spectroscopy [8].The basic idea depends on the fact that the electric field amplitude of an isolated plane progressive harmonic wave propagation through a completely uniform medium, is constant if the medium is free from absorption, and exponentially decreasing in the presence of absorption [7].

A standing wave is created as soon as there is any counter propagating wave which leads to the electric field amplitude to show an oscillatory variation with position. Therefore, coating is an interface, and so there is invariably significant counter propagating energy. The electric field amplitude can exhibit not only significant variation but also considerable magnification compared with the incident field.

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Fry [9] has depicted the variation of the electric field intensity at the surface of metals versus the incident angle of light. Later, France and Ellison [10] have used same picture to explain the mechanism of the enhancement of absorption of thin films on a metal at the grazing angle of incidence. Hansen [11] has derived a method for arbitrary depth for stratified films with N phase using a matrix method [6] in terms of the electric field E and magnetic field H, which includes the calculation of inversion of the matrices. Ohta and Ishida [8] introduce a new algorithm to calculate the electric field intensities for stratified films including metal without the need of the calculation of inverse matrices. However there method was limited to IR spectrum. Macleod [7] have established another computed method when a very thin of absorbing material is embedded in a multilayer to normal incident of light which covered visible and NIR region. In the present work, the electric field intensities for weakly absorbing monolayer coating was computed over a wide range of incidence angle based on the Abele's matrix method [12] in terms of forward and backward propagating electric fields to calculate the reflectance and transmittance . The present study represents another tool for the analysis of absorption in the visible and near-IR spectral region.

2. Basic Theory

The basic matrix technique for the calculations of the properties of an optical coating is actually already contains the electric and magnetic fields so that only a slight modification is required to extract it. The matrix expression, with the usual meaning for the symbols, is [6]:

$$\begin{bmatrix} E' \\ H' \end{bmatrix} = \begin{bmatrix} \cos\delta & \dfrac{i\sin\delta}{y} \\ iy\sin\delta & \cos\delta \end{bmatrix} \begin{bmatrix} E \\ H \end{bmatrix} \tag{1}$$

where E and H are the components of the complex total electric and magnetic field amplitudes parallel to the surface which include the relative phase. For a single propagating plane harmonic wave the magnetic and electric fields are associated through the characteristic admittance, y, of the medium, i.e

$$H = y\,E$$

in terms of B and C

$$\begin{bmatrix} B \\ C \end{bmatrix} = \begin{bmatrix} \cos\delta & \dfrac{i\sin\delta}{y} \\ iy\sin\delta & \cos\delta \end{bmatrix} \begin{bmatrix} 1 \\ y_{exit} \end{bmatrix} \tag{2}$$

The corresponding terms in the other column matrix, are normalized total tangential electric and magnetic fields. The admittances y, too, are normalized so that they are in free space units (1/377 Siemens) rather than SI units. To have absolute values for the total tangential electric field amplitude through the multilayer, it remains simply to give an absolute value to one of the E's. However the easiest, is to put a value on the final tangential component at the emergent interface, which is the interface with the substrate. This is normalized to unity in (1) and is related to the incident irradiance through the transmittance T. If the incident irradiance is I_{inc}, then we can have [7]:

$$\frac{1}{2}\operatorname{Re} E_{exit} \ .H^{*}_{exit} = T.I_{inc} \tag{3}$$

but

$$H_{exit} = y_{exit}\ \xi\ E_{exit} \tag{4}$$

so that

$$E_{exit} = \varepsilon_{exit} = \sqrt{\frac{2T\ .I_{inc}}{y_{exit}\ \xi}} \tag{5}$$

If T is zero then the field must be designated at a different place, usually some convenient interface where there is a non-zero B value.

2.1 Irradiance and Electric Field

Irradiance defined as the mean power per unit area at any point carried by the waves, the orientation of the surface was chosen to maximize the power. The direction of the irradiance is then considered to be parallel to the normal surface. Any other orientation receives a component of the irradiance. The component of irradiance across any unit surface is given by [6]:

$$I=\frac{1}{2} Re\ [EH^{*}] \tag{6}$$

The admittance y at optical frequencies,

$$y= (n-ik)\ \xi \tag{7}$$

ξ being the admittance of free space (1/377 Siemens). Then we can write the irradiance of the wave as

$$I=\frac{1}{2}\ y\xi|\ \varepsilon|^{2} \propto\ |\ \varepsilon|^{2} \tag{8}$$

2.2 Absorption of Light

From (1) and (2), the input and exit irradiances are given by,

$$I_{in} = \frac{1}{2}\operatorname{Re} E'.\ H' \quad and \quad I_{exit} = \frac{1}{2}\operatorname{Re} E.\ H^{*} \tag{9}$$

The irradiance lost by absorption in the layer is the difference between these two quantities. Since the layer is absorbing, the phase thickness δ at oblique incidence is then given by,

$$\delta = \frac{2\pi}{\lambda}(n - ik)d\cos\theta = \alpha - i\beta \tag{10}$$

using Snell's law, the angle of incidence Θ_j at the j[th] layer is :

$$\eta_0 \sin\theta_o = \eta_j \sin\theta_j \tag{11}$$

η_j is the effective refractive index of j[th] layer,

$$\eta_{iS} = n_j \cos\Theta_j \quad \text{for} \quad \textit{S-Polarization} \tag{12}$$

$$\eta_{iP} = n_j / \cos\Theta_j \quad \text{for} \quad \textit{P-Polarization} \tag{13}$$

Equation (10) defines the quantities α and *β*. By extremely thin, we mean that d/λ should be sufficiently small to make both α and β vanishingly small, whatever the size of either n or k. Then substituting equations (3-5) in (1) we can get:

$$\begin{bmatrix} E' \\ H' \end{bmatrix} = \begin{bmatrix} \cos(\alpha - i\beta) & \frac{i\sin(\alpha - i\beta)}{y} \\ iy\sin(\alpha - i\beta) & \cos(\alpha - i\beta) \end{bmatrix} \begin{bmatrix} E \\ H \end{bmatrix} \tag{14}$$

i.e

$$\begin{bmatrix} E' \\ H' \end{bmatrix} = \begin{bmatrix} 1 & \frac{i(\alpha - i\beta)}{(n-ik)\ \xi} \\ i(\alpha - i\beta)(n-ik)\ \xi & 1 \end{bmatrix} \begin{bmatrix} E \\ H \end{bmatrix} = \begin{bmatrix} E + \frac{i(\alpha - i\beta)H}{(n-ik)\ \xi} \\ i(\alpha - i\beta)(n-ik)(\xi E + H) \end{bmatrix} \tag{15}$$

where we have including terms up to the first order only in α and *β*.

The irradiance at the entrance to this layer will then be given by:

$$I_{inc} = \frac{1}{2}\mathrm{Re}\left[\left\{E + \frac{i(\alpha - i\beta)}{(n-ik)\ \xi}\right\}.\ i(\alpha - i\beta)(n-ik)(\xi E + H^*\right]$$

$$=\frac{1}{2}\mathrm{Re}\left[E\ .\ H^{*}+E.-i(\alpha-i\beta)(n-ik)\ \xi H^{*}\right]+\frac{1}{2}\mathrm{Re}\left[\frac{i(\alpha-i\beta)H.H^{*}}{(n-ik)\ \xi})\right] \tag{16}$$

The second term of (10) is zero. This follows since (α - i β)/(n - ik) is real [from (6)] and HH^* is also real. The contents of the square brackets is therefore imaginary and the real part is equal to zero. We can also deduce this result from the fact that H has no interaction with the material. The first term gives

$$I_{inc}=\frac{1}{2}\mathrm{Re}\left[E.H^{*}+E.\ i(\alpha-i\beta)(n-ik)\ \xi E^{*}\right]$$

$$=\frac{1}{2}\mathrm{Re}\left[E.\ H^{*}\right]+\frac{1}{2}\left[E.\ H^{*}\right]\frac{1}{2}\left[(\alpha k+\beta n)\ \xi E.\ E^{*}\right] \tag{17}$$

where

$$\alpha k+\beta n=(4\ \pi\ nkd/\lambda)\quad \text{and}\quad E.E^{*}=\varepsilon^{2} \tag{18}$$

Equation (17) show that the irradiance that has been absorbed is given by the difference between the irradiance incidents on the thickness element I_{inc}, and that emerging on the exit side I_{exit} , that is:

$$I_{absorbed}=\frac{2nkd}{\lambda}\ .\xi.\ \varepsilon^{2} \tag{19}$$

where the magnitude of the absorbed energy is directly proportional to the multiplication of n and k. Both must be nonzero for absorption to occur. The absorption will be small for a metal with vanishingly small n, and a dielectric with vanishingly small k.

3. Experimental Work

SnO_2 thin films were deposited by chemical spray pyrolysis (CSP) technique onto glass substrates from aqueous solution of 0.1 M of $SnCl_4.5H_2O$. For a careful cleaning of glass substrate, the substrates were initially boiled in chromic acid for 15 minutes, then it was washed with distilled water. These substrates were further treated in ultrasonic bath for a further 15 minutes prior to deposition. The optimized preparation conditions being arrived at the following: substrate temperature was kept at 500 ^{o}C, and controlled within ±5 ^{o}C through a chromel-alumel thermocouple as a sensor for the temperature controller. The distance between nozzle and substrate was about 30 cm, the spraying rate was maintained at 5 ml/min, compressed air was used to atomized the solution containing the precursor compounds through a spray nozzle over the heated substrate. Weighting method was used to measure the thickness of the deposited films and was found to be in the range of about 0.35±0.05 μm. The obtained films exhibit good adherence to substrate surface. Transmittance and absorbance were recorded with a Shimadzu 1650 double beam UV/Vis spectrophotometer in the wavelength range (350 -900) nm.

4. Results and Discussion

4.1 Normal Incidence of Light

The profile of normalized electric field intensity vs. film depth was computed with the aid of TF calc software package [13].

The refractive index n and extinction coefficient k was computed from the measurement of film transmittance (thickness of about 400 nm) within the spectral region (350-900 nm) taken into account the effect of dispersion. Fig. 1 and 2 illustrates the dispersion phenomena and the transmittance of SnO_2.

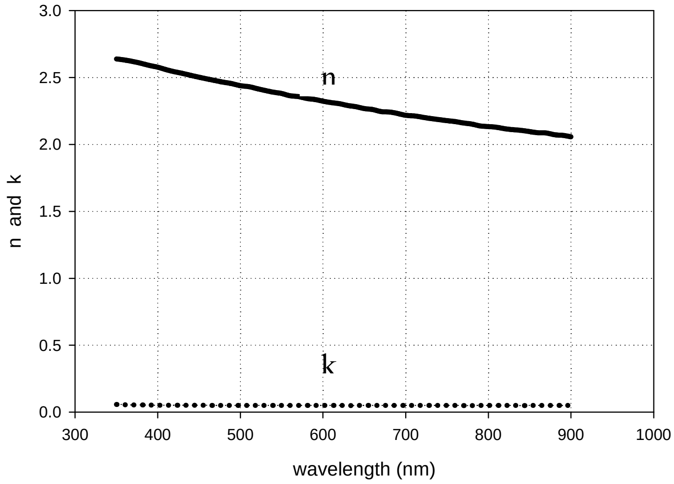


Fig. 1: Dispersion phenomena of SnO_2 (normal incidence).

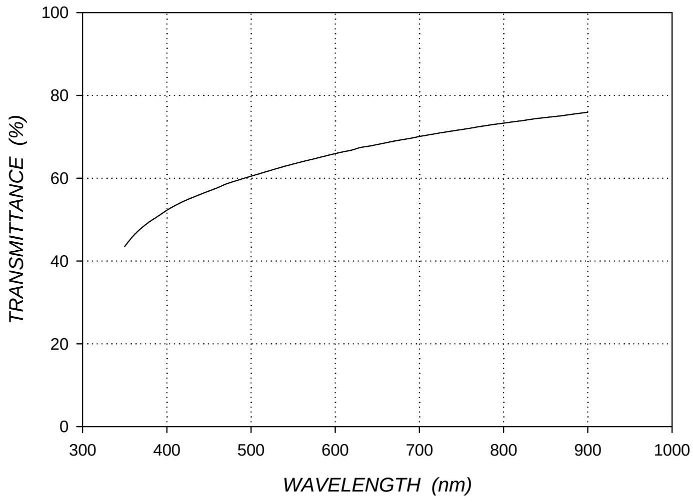
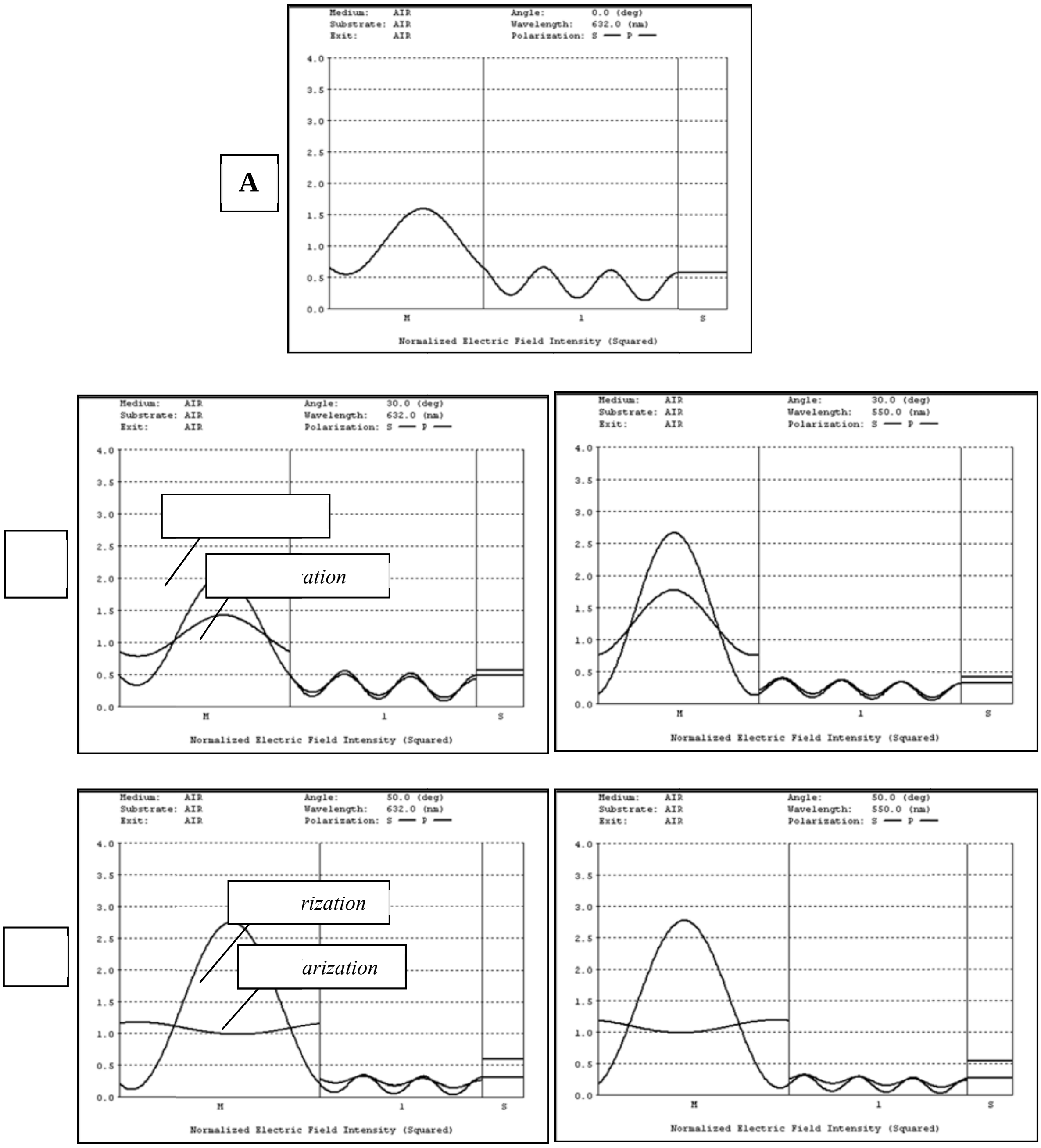


Fig. 2: Measured transmittance of (thickness of about of 400 nm) against wavelength.
The reference wavelength is 632 nm (normal incidence).

4.2 Oblique Incidence of Light

The effect of angle of incidence of light over the angle range (0-90º) and reference wavelengths (550 nm and 632 nm) on the electric field distribution were also investigated and shown in Fig. 3. The profile was computed over three zones:

M represent the incident medium,
1 the monolayer,
S the substrate (may be air)



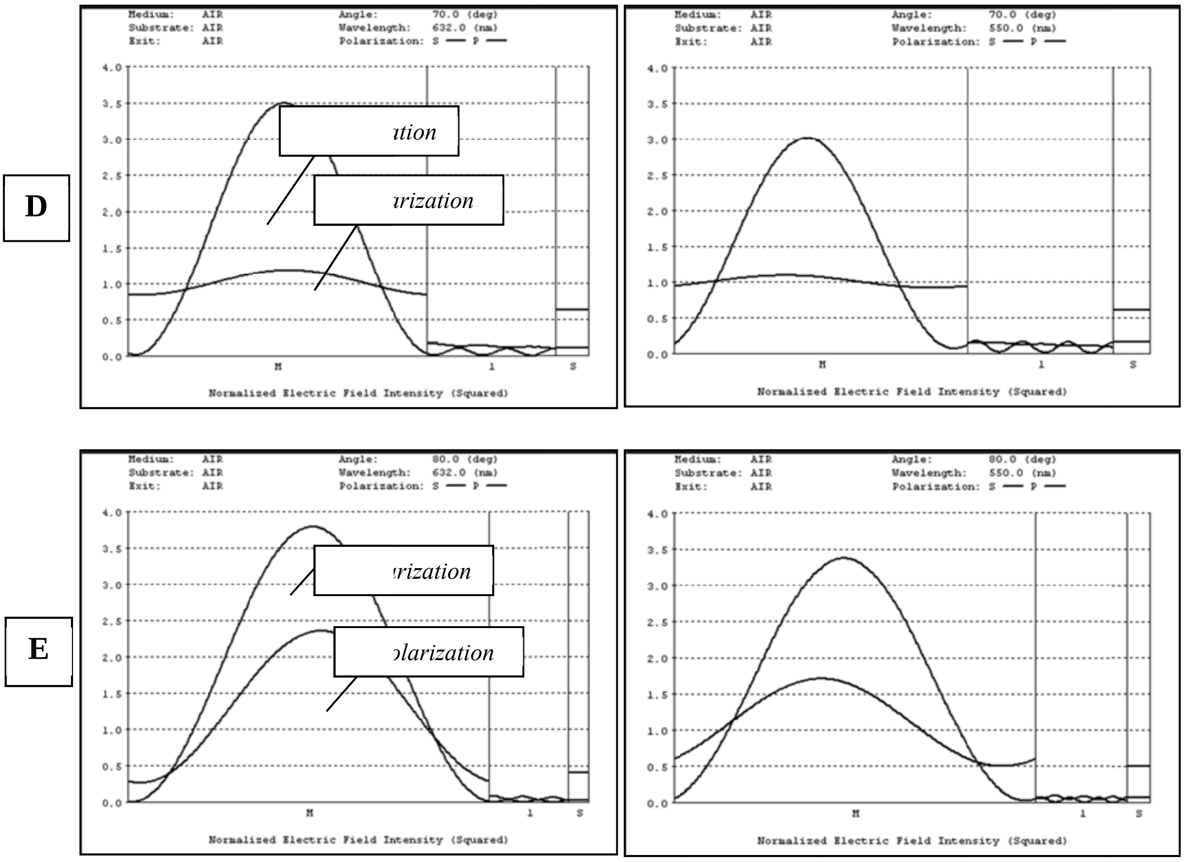


Fig. 3: The depth profile of electric field distribution of oblique incident of light at for two reference wavelengths 550 nm and 632 nm.

It is clear from figure that high reduction, low sensitivity to polarization was achieved, regardless the reference wavelength. This behaviour may be due the fact that the interface in layer coatings is usually exhibit a greater concentrations of defects than elsewhere which made it susceptible to absorption and scattering to a great extent.

5. Conclusions

From the results one can conclude the following:

- The electric field description of the light absorbed at a certain thickness to the total absorption can be evaluated using the profile of the field along the direction of the depth.
- It is possible to reduce the electric field everywhere using a monolayer of weakly absorbing layer.
- The best selection of layer thickness reduces the field at the interface to a great extent.
- The Present study offers a useful tool in the understanding of the mechanism of light absorption in many applications in spatially reflection spectroscopy.

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