

Effect of Impurity Concentration on the Depth Profile of the Electric Field within Monolayer Thin Film

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The effect of impurity concentration ratios on the depth profile of electric field within monolayer film is presented. SnO₂ monolayer thin film material was prepared and doped with Co using spray chemical pyrolysis. The concentration ratios of impurity were 1 %, 3 %, 5 % and 7 %. The analysis utilizes matrix formulas based on Abele's formulas from the calculation of reflectance and transmittance. Present study gives an information to contamination sensitivity in optical coating issue.

Keywords: Electric field intensity, Matrix formulas, Contamination sensitivity.

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1. INTRODUCTION

At optical frequencies, it is the electric field of the light that is responsible for many interactions with material. An understanding of the distribution of electric field in an optical coating leads immediately to an understanding of many important effects including absorption, scattering and contamination sensitivity [1-5]. For a multilayer system, the profile of the electric field system has played an important role in the analysis of various kinds of spectroscopy, spatially reflection spectroscopy [6]. 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 [5]. A standing wave is created as soon as there is any counter propagating wave and then the electric field amplitude shows 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.

Fry [7] first depicted the variation of the electric field intensity at the surface of metals versus the incident angle of the light. Later, Francis and Ellison [8] 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 [9] derived a method for arbitrary depth for stratified films with N phase using a matrix method [4] in terms of the electric field E and magnetic field H , which includes the calculation of inversion of the matrices. Ohta and Ishdia [6] introduce a new algorithm to calculate the electric field intensities for stratified films including metal without need to the calculation of inverse matrices. There method was limited to IR spectrum. Macleod [5, 10, 11] assume that the contamination is presented as an extremely thin layer of absorbing material and the contamination sensitivity begins with his idea of electric field distribution.

In this report the sensitivity of electric field intensity profile to the change in impurity concentration was study based on Abele's matrix method [12] in terms of

forward and backward propagating electric fields to calculate the reflectance and transmittance. Such idea may be useful in contamination sensitivity in optical coating studies.

2. BASIC THEORY

The basic matrix technique for the calculation of the properties of an optical coating actually contains already the electric and magnetic field so only a slight modification is required to extract it. The matrix expression, with the usual meaning for the symbols, is [4]:

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

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.

$$H = y E$$

in terms of B and C

$$\begin{bmatrix} B \\ C \end{bmatrix} = \begin{bmatrix} \cos \delta & \frac{i \sin \delta}{y} \\ iy \sin \delta & \cos \delta \end{bmatrix} \begin{bmatrix} 1 \\ y_{ext} \end{bmatrix}. \quad (1)$$

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 / 377siemens) 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. 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 [5].

$$0.5 \operatorname{Re} E_{\text{exit}} \cdot H_{\text{exit}}^* = T \cdot I_{\text{inc}}$$

but

$$H_{\text{exit}} = y_{\text{exit}} \zeta E_{\text{exit}},$$

so that

$$E_{\text{exit}} = \varepsilon_{\text{exit}} = \sqrt{\frac{2T \cdot I_{\text{inc}}}{y_{\text{exit}} \zeta}}.$$

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 being chosen to maximize the power. The direction of the irradiance is then considered to be parallel to the surface normal. Any other orientation receives a component of the irradiance. The component of irradiance across any unit surface is given by [4]:

$$I = 0.5 \operatorname{Re} [EH^*], \quad (2)$$

The admittance y at optical frequencies,

$$y = (n - ik)\xi,$$

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

$$I = 0.5Y\zeta |\varepsilon|^2 \propto |\varepsilon|^2.$$

2.2 Absorption of Light

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

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

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

$$\delta = \frac{2\pi}{\lambda} (n - ik)d\theta = \alpha - i\beta. \quad (3)$$

Equation (3) 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 (3) in (1),

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

i.e.

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

where we are 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

$$I_{\text{in}} = \frac{1}{2} \operatorname{Re} \left[\{E + i(\alpha - i\beta) / (n - ik)\zeta\} i(\alpha - i\beta)(n - ik)(\zeta E + H^*) \right] \\ A = 1 - R - T \quad (4)$$

The second of the two terms in (4) is zero. This follows since $(\alpha - i\beta) / (n - ik)$ is real [from (4)] and HH^* is also real. The content of the square brackets is therefore imaginary and the real part, zero. We could also deduce this from the fact that H has no interaction with the material. The first term gives

$$I_{\text{in}} = \frac{1}{2} \operatorname{Re} [E \cdot H^* + E \cdot i(\alpha - i\beta)(n - ik)\zeta H^*] = \\ = \frac{1}{2} \operatorname{Re} [E \cdot H^*] + \frac{1}{2} [E \cdot H^*] \frac{1}{2} [(\alpha k + \beta n)\zeta E \cdot E^*] \quad (5)$$

where

$$\alpha k + \beta n = (4\pi nkd / \lambda) \quad \text{and} \quad E \cdot E^* = \varepsilon \quad (6)$$

Equation (5) shows that the irradiance that has been absorbed is given by the difference between the irradiance incident on the thickness element I_{in} , and that emerging on the exit side I_{exit} , that is:

$$I_{\text{absorbed}} = (2nk d) / \lambda \cdot \zeta \cdot \varepsilon^2,$$

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 both for a metal with vanishingly small n and a dielectric with vanishingly small k absorption.

2.3 Potential transmittance and absorption

Potential transmittance [5], ψ , of any element of a coating system is defined as the ratio of the output to the input irradiance, the input being the net irradiance rather than that incident. Potential transmittance has several advantages over transmittance when dealing with absorbing systems because it can completely avoid any problems associated with the mixed Poynting vector in absorbing media. The potential transmittance of a complete system is simply the product of the individual potential transmittances.

$$\psi = \frac{I_{\text{exit}}}{I_{\text{in}}}$$

$$\psi = \psi_1 \psi_2 \psi_3 \psi_4 \psi_5 \dots \psi_q \quad (8)$$

with the eventual overall transmittance given by

$$T = 1 - R_{\text{system}} \quad (9)$$

The potential transmittance of the thin elemental film is given by

$$\psi = \frac{I_{\text{exit}}}{I_{\text{in}}} = 1 - \frac{I_{\text{absorbed}}}{I_{\text{in}}} = 1 - A, \quad (10)$$

where A is the potential absorptance. But

$$I_{in} = \frac{1}{2} \zeta \cdot \text{Re} \cdot Y \cdot \varepsilon^2, \quad (11)$$

where Y is given in free space units. Then

$$\psi = 1 - A = 1 - \frac{2\pi nkd}{\lambda} \frac{2}{\text{Re}Y}, \quad (12)$$

and so

$$A = 2 \cdot \frac{2\pi nkd}{\lambda} \cdot \frac{1}{\text{Re}Y}. \quad (13)$$

To move from potential absorption to absorption is straightforward when the absorption is confined to a very thin layer, the rest of the multilayer being essentially transparent. Then the absorption, A , is given by:

$$A = 1 - R - T. \quad (14)$$

3. RESULTS AND DISCUSSION

3.1 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 $\text{SnCl}_4 \cdot 5\text{H}_2\text{O}$. For the careful cleaning of glass substrate, the substrates were initially boiled in chromic acid for 15 min, washed with distilled water. These substrates were further treated in ultrasonic bath for 15 min prior to deposition. The optimized preparation conditions being arrived at the followings: substrate temperature was kept at 500°C and controlled within $\pm 5^\circ\text{C}$ 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 atomize 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 in the range of $0.35 \pm 0.05 \mu\text{m}$. 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.

3.2 Electric Field Intensity Profile

The profile of normalized electric field intensity vs. film depth was computed with the aid of TF calc. software package [13]. SnO_2 was prepared as thin film using the chemical spray pyrolysis. The thickness of prepared thin film was 400 nm evaluated using the weighting method. The profile was computed over three zones:

M represent the incident medium;

1 monolayer;

S the substrate (may be air).

as shown in Fig. 1. The reference wavelength was 632 nm.

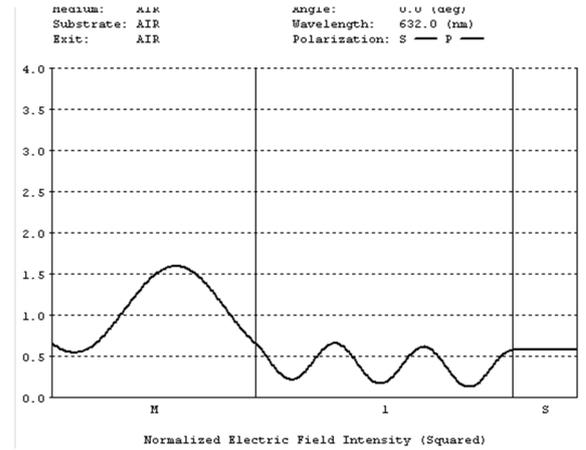


Fig. 1 – The depth profile of electric field distribution for SnO_2 thin film of thickness 400 nm

The refractive index n and extinction coefficient k was computed from the measurement of film transmittance within the spectral region (350-900 nm) taken into account the effect of dispersion. Fig. 2 and 3 illustrate the dispersion phenomena and the transmittance of SnO_2

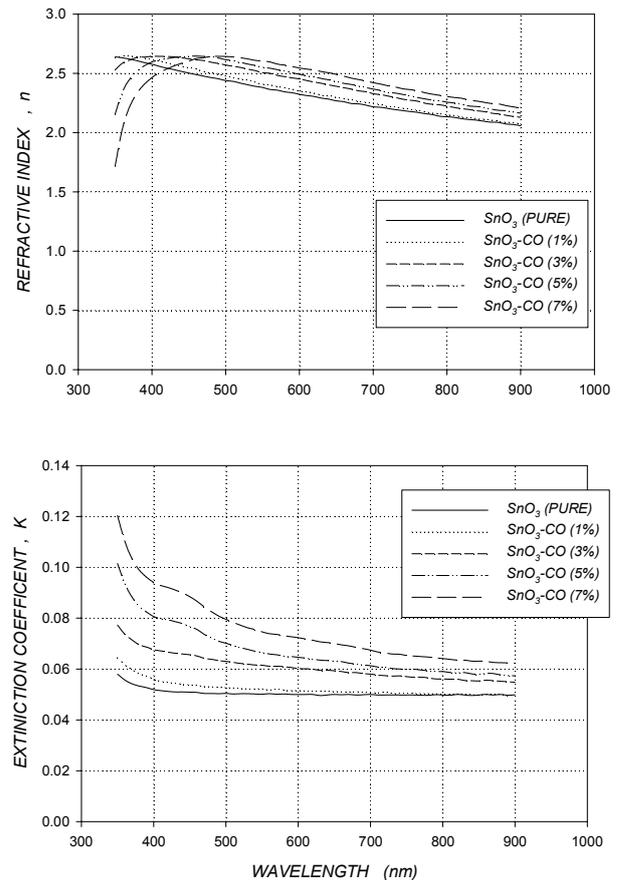


Fig. 2 – Dispersion phenomena of n and k for SnO_2 with impurity concentration (1 %, 3 %, 5 % and 7 %)

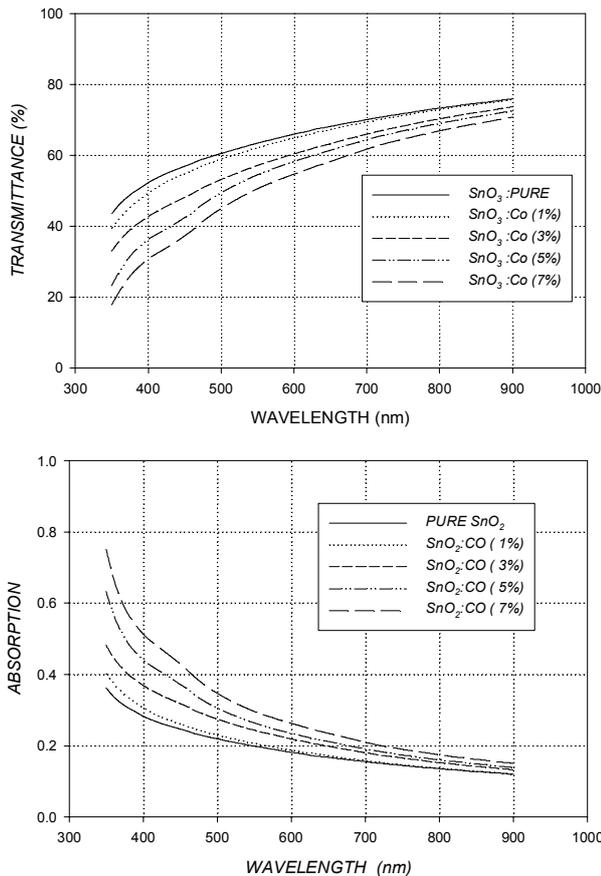


Fig. 3 – Measured transmittance and absorption vs avelength of SnO₂ of various impurity concentration

3.3 Shifting in Electric Field Intensity Profile

The effect of impurity concentration ratio on the electric field intensity profile versus film depth were also investigated in Fig. 4 as extended of the second zone.

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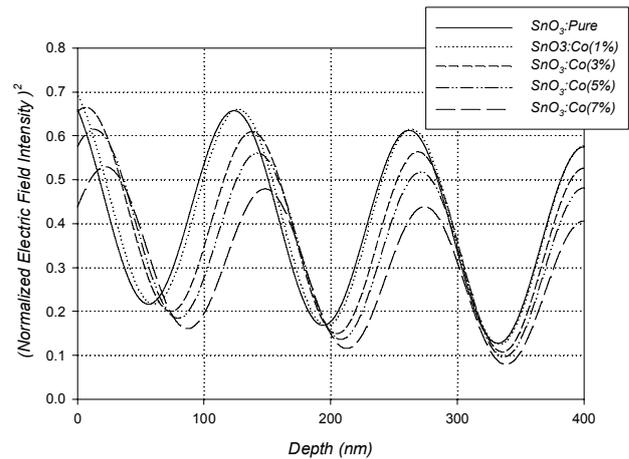


Fig. 4 – The extended 2nd zone of depth profile of electric field distribution for different impurity concentration ratios

It is clear from figure that maxima of electric field were reduced in its value in addition to shifting in their depth position as concentration ratio increased. This behaviour may be due the fact that the interface in a layer coating usually exhibit greater concentrations of defects than elsewhere and then susceptible to absorption and scattering to great extent.

4. CONCLUSIONS

From the results one can conclude the following:

1. 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.
2. It is possible to reduce the electric field everywhere using monolayer of weakly absorbing layer.
3. The best selection of layer thickness reduces the field at the interface to a great extent.
4. Present study offers useful tool in understanding the mechanism of light absorption in many applications spatially contamination sensitivity.