



Optical Modeling Of Fluorine Doped Tin Oxide Films For Spectrally Selective Applications

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Abstract

SnO₂: F films are widely used for solar cell applications as the front electrode as well as other applications such as electrochromics and displays. Optical design of these and other applications need the knowledge of optical constants. In this study we used the dielectric constant of a combined Drude and Lorentz to model the optical behavior of SnO₂: F. To do this, we used the fitting parameters from existing literature. From the model we got n and k values which we inserted into Fresnel R and T calculator and computed R and T spectra over the 300nm -2500nm wavelength range using Fresnel's equations. We plotted n, k, T and R for different values of plasma frequency, ω_p and damping parameter, Γ . The films exhibited very high visual transmittance and high infrared reflectance. The results implied the possibility of the films to be employed as spectrally selective coating materials.

KEY WORDS: Optical constants, damping parameter, thin film, Drude-Lorentz model.

1. Introduction

Transparent conductors are materials that possess both good electrical conductivity and optical transparency in the visible portion of the electromagnetic spectrum. A wide band gap (~ 3 eV) is needed for visible transparency. A combination of transparency and conduction can be achieved in two different types of materials[1]:- (1) Extremely thin films of metals especially Ag, Au or Cu on glass or (2) among wide-band gap oxide semiconductors such as fluorine-doped tin oxide (FTO), antimony-doped tin oxide (ATO), tin-doped indium-oxide (ITO), niobium-doped titanium oxide (TNO) and aluminium-doped zinc oxide (AZO). Wide-band gap oxide semiconductors are in most cases referred as transparent conducting oxides (TCOs).

TCOs have been employed technologically for more than a half-century in applications requiring both high conductivity and optical transparency. Some TCO applications include transparent electrodes for flat-panel displays[2], liquid crystal displays (LCDs)[3], organic light-emitting diodes (OLEDs)[4], as coatings for heat reflective windows i.e. thermal management for window glass[5], electrochromic (smart) windows[6], solar cells[7], electromagnetic shielding[8],



functional glasses[9], electrochemical cells[10] and gas sensors[11]. TCOs are also applicable to transparent optoelectronics because they have the unique features of optical transparency in the visible region and controllable electrical conductivity, from almost insulating to degenerate semi-conducting ($\sim 10^4$ S/cm) behaviour.

Tin oxide, among the semiconductors, demonstrates special features in chemical inertness [12], stability to heat treatment and mechanical hardness[13]. Further, tin oxide films are highly transparent in the visible range [14]. It also has a direct band gap of approximately 3.6eV[15] which makes it possible to have a wide range of applications in electronic devices. In order to improve its optical and electrical properties, tin oxide films need to be doped with the right dopants such as fluorine, cadmium, molybdenum and antimony[16]. Among these dopants fluorine is found to be the best dopant for tin oxide since the radii of O^{2-} and F^- are similar hence there will be no mismatch of lattices during doping[16].

Thin films of transparent oxide semiconductors, such as F-doped tin oxide, are widely investigated due to their high optical transmission, electrical conduction, and infrared reflection. These properties make these films to find wide applications in optoelectronic devices, hybrid microelectronics, photo thermal conversion and direct energy conversion devices particularly in conductor-insulator- semiconductor solar cells. Fluorine-doped tin oxide has a work function of about 4.9eV, electron concentration in the order of 10^{20}cm^{-3} , an approximate minimum resistivity of about $200 \mu\Omega \text{cm}$ and a visible absorption coefficient of about 0.04[17].

Thin film surface coatings are most widely employed for the efficient conversion of solar radiation into other useful forms, such as thermal energy for heating and cooling applications; and electrical energy by direct conversion using photovoltaic cells. The other current applications of such optical coatings include: transparent heat mirrors[18], antireflection coatings[19], architectural coatings[20], photo-thermal converters[20], and photo- catalysis[21].

Invar Hamberg (1984) in his thesis[22], reported that for the material to be used as spectrally selective coating material, it must meet three conditions: (1) should have a significantly wide band gap in order for the material to guarantee the key absorption edge to be below a solar wavelength length of approximately 300nm; (2) a prospect to dope the material to attain a high free carrier concentration leading to a high infrared reflectivity; (3) a limited absorption between the key absorption edge and the plasma wavelength, to guarantee a high luminous transmittance. Also, MghendiMwamburi in his thesis[23] reported separately that for a material to be used as spectrally selective reflector (SSR)it must exhibit very high visual transmittance and high infrared reflectance. Furthermore, he suggested that the region of the plasma absorption peak must be positioned in the part of the solar spectrum with photon energies lower than the band gap of the given solar cell. Spectrally selective films are those that allow peculiarly selected portions of light spectrum to pass through a medium while blocking some i.e. their transmission and/or reflection properties are regulated for selected and controlled packages of thermal radiation fluxes[24]. The conditions aforementioned necessitated the need to investigate a thin film that would meet all the conditions. The aim of the study was to model SSR films.

There are apparently many methods that have been employed to study the optical behavior of SnO_2 : F films as it is the case in numerous publications. The appropriate investigation of the optical properties of the films requires the finding of optical constants such like the extinction coefficient, k and refractive index, n over the desired wavelength range. In the present work we

employed the dielectric constant of a combined Drude and Lorentz to investigate the optical properties of SnO₂: F films.

1.1 Theoretical Background

The absorption and refraction of a medium can be described by a single quantity called complex refractive index[25]. This is usually given the symbol \tilde{n} or N and is defined as shown in equation (1).

$$N = n + ik \tag{1}$$

The real part of N namely n is the same as the normal refractive index defined in equation (2). The imaginary part of N, namely k, is called the extinction coefficient which is related with absorption coefficient by equation (3).

$$n = \frac{c}{v} \tag{2}$$

$$\alpha = \frac{2\omega k}{c} = \frac{4\pi k}{\lambda} \tag{3}$$

We can relate the complex refractive index of any medium to complex dielectric constant by using equation 4. This shows us that if n is complex, then ϵ must also be complex.

$$N^2 = \tilde{\epsilon}_r = \epsilon_1 + i\epsilon_2 \tag{4}$$

By comparing equations (1) and (4), explicit relationships between the real and imaginary parts of N and $\tilde{\epsilon}$ can be computed and the resulting equations are as shown in equations (5) and (6).

$$\epsilon_1 = n^2 - k^2 \tag{5}$$

$$\epsilon_2 = 2nk \tag{6}$$

Here n, k, ϵ_1 and ϵ_2 are referred to as the optical ‘constants’ of the medium. They are referred to as constants due to historical reasons otherwise they are functions of wavelength. ϵ_1 is related to the polarizability and ϵ_2 to the true optical absorption. These values depend on the photon energy, $E = \hbar\omega$. Further, these optical constants, for any medium, can be calculated from a Drude-Lorentz model given in equation (7). The individual Drude and Lorentz models are as given in equations (8) and (9) respectively.

$$\epsilon = \epsilon_\infty - \frac{\omega_D^2}{\omega^2 + i\Gamma_D\omega} + \frac{\omega_L^2}{(\omega_0^2 - \omega^2) - i\omega\Gamma_L} \tag{7}$$

$$\epsilon'_r(\omega) = 1 - \omega_p^2 \frac{1}{\omega^2 + \Gamma^2}, \quad \epsilon''_r(\omega) = \omega_p^2 \frac{\Gamma/\omega}{\omega^2 + \Gamma^2} \tag{8}$$



$$\tilde{\epsilon} = 1 + \frac{Ne^2}{\epsilon_0 m (\omega_0^2 - \omega^2) - i\omega\Gamma} \quad [9]$$

The Fresnel equations that are usually used to work out the transmittance and reflectance of the films are as shown in equations 10-19[26].

$$t_p = \frac{2N_1 \cos\theta_1}{N_1 \cos\theta_2 + N_2 \cos\theta_1} \quad [10]$$

$$t_s = \frac{2N_1 \cos\theta_1}{N_1 \cos\theta_1 + N_2 \cos\theta_2} \quad [11]$$

$$r_p = \frac{N_2 \cos\theta_1 - N_1 \cos\theta_2}{N_2 \cos\theta_1 + N_1 \cos\theta_2} \quad [12]$$

$$r_s = \frac{N_1 \cos\theta_1 - N_2 \cos\theta_2}{N_1 \cos\theta_1 + N_2 \cos\theta_2} \quad [13]$$

And at normal incidence the equations become:

$$r_1 = \frac{N_2 - N_1}{N_2 + N_1}, r_2 = \frac{N_3 - N_2}{N_3 + N_2} \quad [14]$$

$$t_1 = \frac{2}{N_1 + N_2}, t_2 = \frac{2N_2}{N_2 + N_3} \quad [15]$$

Hence, we can find r and t according to:

$$r = \frac{r_1 + r_2 e^{-2i\partial}}{1 + r_1 r_2 e^{-2i\partial}} \quad [16]$$

$$t = \frac{t_1 t_2 e^{-i\partial}}{1 + r_1 r_2 e^{-2i\partial}} \quad [17]$$

where the phase shift, ∂ , is given by

$$\partial = -\frac{2\pi}{\lambda} N_2 d \cos\theta_2, \text{ which for normal incidence becomes; } \partial = -\frac{2\pi N_2}{\lambda} d \quad [18]$$

and r_1 and t_1 are the Fresnel coefficients for the boundary between air and film and r_2 and t_2 are the corresponding coefficients for the boundary between film and substrate.

With the Fresnel equations above we can calculate the intensity reflectance, R, and the intensity transmittance, T, according to:

$$R = r r^* \quad \text{and} \quad T = \text{Re} \left(\frac{N_3}{N_1} \right) t t^* \quad [19]$$

where r^* is the conjugate of the amplitude reflectance and t^* is the conjugate of the amplitude transmittance.



2. The Simulation Method.

The Drude–Lorentz modeling of optical spectral of SnO₂: F films was simulated using equation (7) with a commercial MATLAB computer program. To do this, we used the fitting parameters from existing literature shown in table (1) which we inserted into the MATLAB program and got n and k values as well as real part (ϵ_1) and imaginary part (ϵ_2). We inserted each pair of n and k values into Fresnel equation R & T calculator together with Fresnel’s equations (equations 10-19) to compute R- and T- spectra of SnO₂: F films at different film thicknesses, d and for the various doping concentrations, n_e, over 300 – 2500nm wavelength range. We used different values of plasma frequencies, ω_p (s⁻¹) shown in table 2. All the simulation was done by using the commercial MATLAB computer program

The figures shown below represent the modeled optical data for the different samples i.e. S_A, S_B, S_C, S_D, S_E, S_F and S_G. S_A is the undoped sample whereas S_G is the heavily doped sample. The dopant concentration was increased gradually by varying the value of ω_p (s⁻¹) as depicted in table 2.

Table 1. Drude and Lorentz parameters for undoped and F-doped tin oxide

	ϵ_∞	ω_p (x`10 ¹⁴ s ⁻¹)	Γ_D (eV)	ω_p (s ⁻¹)	Γ_L (eV)	ω (s ⁻¹)
SnO ₂	4.0	-	-	1.56x`10 ¹⁴	0.5064	8.19x`10 ¹⁴
SnO ₂ : F	3.19	1.43	0.167	24.67x`10 ¹⁵	0.1275	1.27x`10 ¹⁵

Table 2: Values of plasma frequencies, ω_p (s⁻¹) used to calculate the optical constants in a combined Drude and Lorentz model.

Sample	S _A	S _B	S _C	S _D	S _E	S _F	S _G
ω_p (x`10 ¹⁴ s ⁻¹)	0	1.43	2.02	2.85	3.49	4.03	5.71

3. Results and Discussion

3.1 Optical Studies

In order to compare the reflectance and transmittance of SnO₂ thin films with various F-doping levels, the optical R- and T-spectra in the UV-VIS-NIR region of the samples were computed and the results are as shown in Figures 1 (a), (b), (c) and (d). The various film thicknesses shown in figures 1 (a), (b) and (c) are meant to magnify the optical properties of the graphs in the near IR for easy comparison.

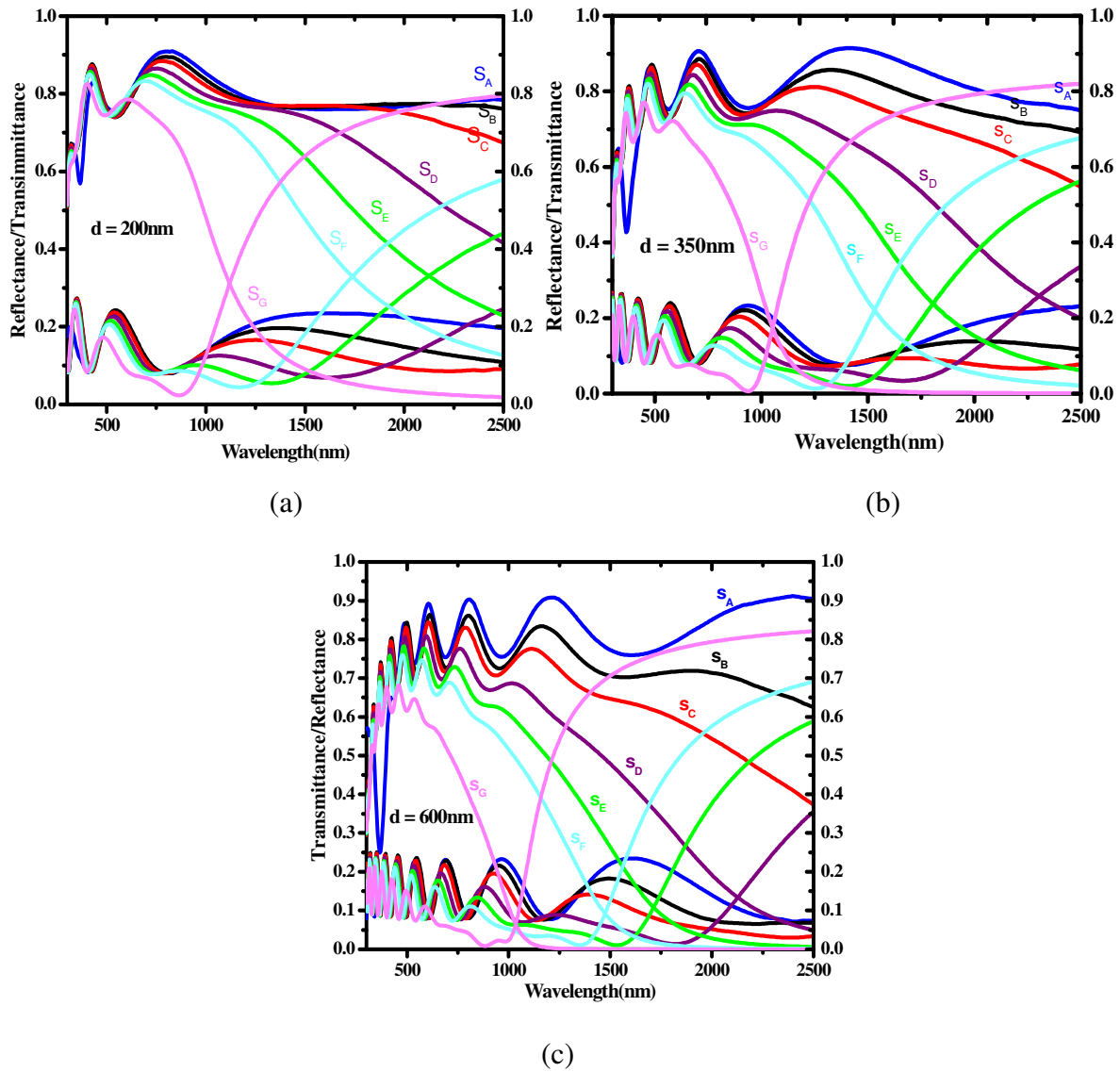


Figure 1 Spectral reflectance and transmittance for various F-doping concentrations at film thickness (a) $d = 200\text{nm}$, (b) $d = 350\text{nm}$, (c) $d = 600\text{nm}$.

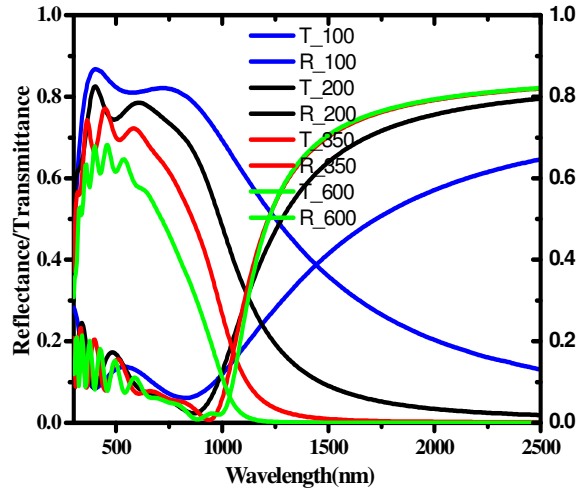


Figure 1(d) Spectral reflectance and transmittance of the highly doped sample (S_G) showing various film thicknesses. The films thicknesses were 100nm, 200nm, 350nm and 600nm.

It was clearly noted from the figures 1 (a), (b) and (c) that the films exhibited high transparency in the visible region but in near IR region the transparency started to decrease with increase in F-doping concentration. The decrease in transmittance is due to reflection by the free electron in the highly F-doped SnO_2 . This further illustrates that although doping improves the free carrier concentration thus the conductivity, it jeopardizes the transparency of the film. Thus, there is a demand that a compromise between the optical properties and electrical properties should be attained for TCOs. On the other hand, reflectance increases in the near infrared region with increasing F doping concentration to a maximum of 81.8% for the highly doped sample. The reduction of transmittance and the rise of reflectance at near infrared indicate that the samples start to conduct. These observations are perfectly in agreement with other already reported work [27]. The transmittance and reflectance behavior of the films at various F-doping levels illustrates that doping improves the optical properties as well as conductivity of the films to a significant degree.

The shifts in the transmittance and reflectance fringes of the doped samples proposes that doping leads to a slight change in the thickness and in the refractive index of the films. This can be verified by using the number of interference fringes as given in equation 20 [28] and by Swanepoel formula given in equation 21 [29] respectively.

$$d = \frac{\lambda_1 \lambda_2}{2(\lambda_1 n_1 - \lambda_2 n_1)} \tag{20}$$

where n_1 and n_2 are refractive indices at two adjacent maxima (or minima) at λ_1 and λ_2 respectively.

$$n = \sqrt{N + \sqrt{N^2 - S^2}} \tag{21}$$

where



$$N = 2S \frac{T_M - T_m}{T_M T_m} + \frac{S^2 + 1}{2} \tag{22}$$

and S is the refractive index of the substrate, T_M and T_m represents the maximum and minimum transmittance envelopes at the fringes.

It was also noted from the figures that there is the cross over between R and T curves which shifts towards the visible range with increasing fluorine doping. These cross over show the position of the plasma wavelength. The plasma frequency ω_p , which according to classical Drude is as given in equation 23, is used to characterize the reflection by the free carriers. Using equation 23 we computed the carrier concentration, n_c of the samples and their corresponding values were recorded as shown in tables 3 and 4.

$$\omega_p = \left(\frac{n_c e^2}{\epsilon_0 \epsilon_\infty m^*} \right)^{\frac{1}{2}} \tag{23}$$

where ϵ_0 is the permittivity of free space, ϵ_∞ the high-frequency dielectric constant and m^* the effective conduction –band mass. In this paper we assumed the value of $m^* = 0.25m_e$ [30] where m_e is the free electron mass.

The Spectral reflectance and transmittance at different film thicknesses were also investigated and the results are as shown in figure 1(d). The film thicknesses were increased from 100nm up to 600nm. It was clearly noted that increasing film thickness leads to an increase in reflectance and a decrease in transmittance. This observation is an evidence that the film thickness significantly affects the transmittance and reflectance characteristics.

The optical constants i.e. spectral refractive index $n(\lambda)$, extinction coefficient $k(\lambda)$, real (ϵ_1) and imaginary (ϵ_2) parts of the dielectric constant for SnO₂ and SnO₂:F films are reported as shown in figures 2, 3, and 4. From figure 2 it was clear that the undoped film shows a dielectric behavior with $n = 2$ over the 300nm -2500nm wavelength range. This value is well comparable with 1.98 already reported [13]. This refractive index value makes the transparent semiconducting tin oxide suited to be employed as an inherent antireflection coating on silicon [30].

From figures 3 and 2 it was clearly noted that $k(\lambda)$ increases with increase in wavelength whereas $n(\lambda)$ shows a decrease towards higher wavelengths. These effects are more pronounced with increasing F-doping concentration. This behavior was as expected for the case of metallic materials [31] and it may be associated to both shift of the plasma edge as well as the Burstein-Moss shift of the band edge [32].

Figures 4 show that ϵ_1 decreases with increasing fluorine doping concentrations while ϵ_2 shows an increase. It was also clearly noticed that the real dielectric constant, ϵ_1 is substantially negative in the range of high reflectance. This can be understood to mean that high negative values of ϵ_1 match with a phase relation between the light and polarization. This relation aligns

the polarization in opposite direction to the incoming electromagnetic wave and hence high reflectance.

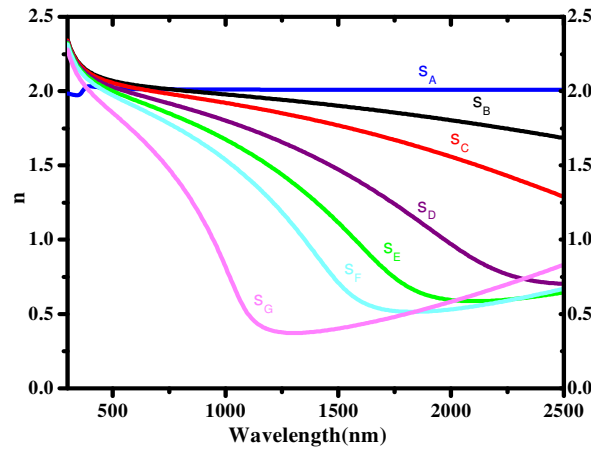


Figure 2. Spectral refractive index, $n(\lambda)$ for the SnO_2 and $\text{SnO}_2:\text{F}$ for various levels of F-doping concentration.

Comparing figures 2 and 4(a), it was clearly noted that the real refractive index, n , is small over the region where ϵ_1 is negative. This makes the material to be optically metal-like[33]. This further informs us that when ϵ_1 is negative, the optical constants are $n \approx 0$ and $k = \sqrt{-\epsilon}$ corresponding to an exponentially damped field without energy loss, $\epsilon_2 = 0$ [34].

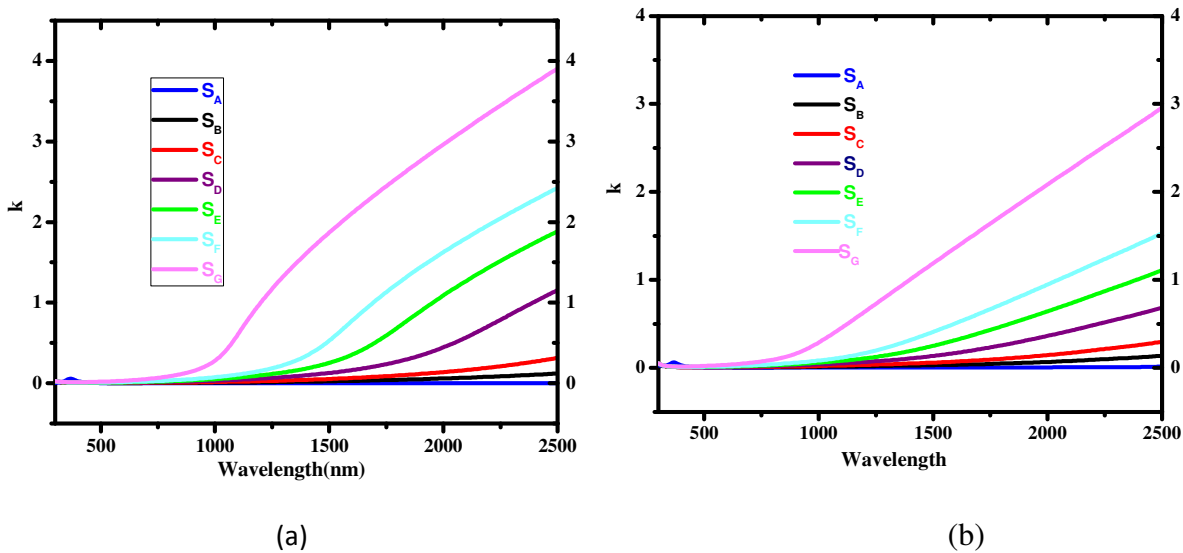


Figure 3. Spectral extinction coefficient, $k(\lambda)$ for the SnO_2 and $\text{SnO}_2:\text{F}$ showing values of k calculated from (a) Drude-Lorentz model and (b) Hong's formula at $d = 350\text{nm}$.

Figures 3 show a comparison of spectral extinction coefficient, $k(\lambda)$ between the various values of k computed from Drude - Lorentz model and that from Hong's formula. The Hong's formula

that was used to compute the k values is as shown in equation 24[35]. The slight difference observed may be due approximation and assumption nature of the formulae.

$$\frac{1-R}{T} = \exp\left(\frac{4\pi kd}{\lambda}\right) \quad [24]$$

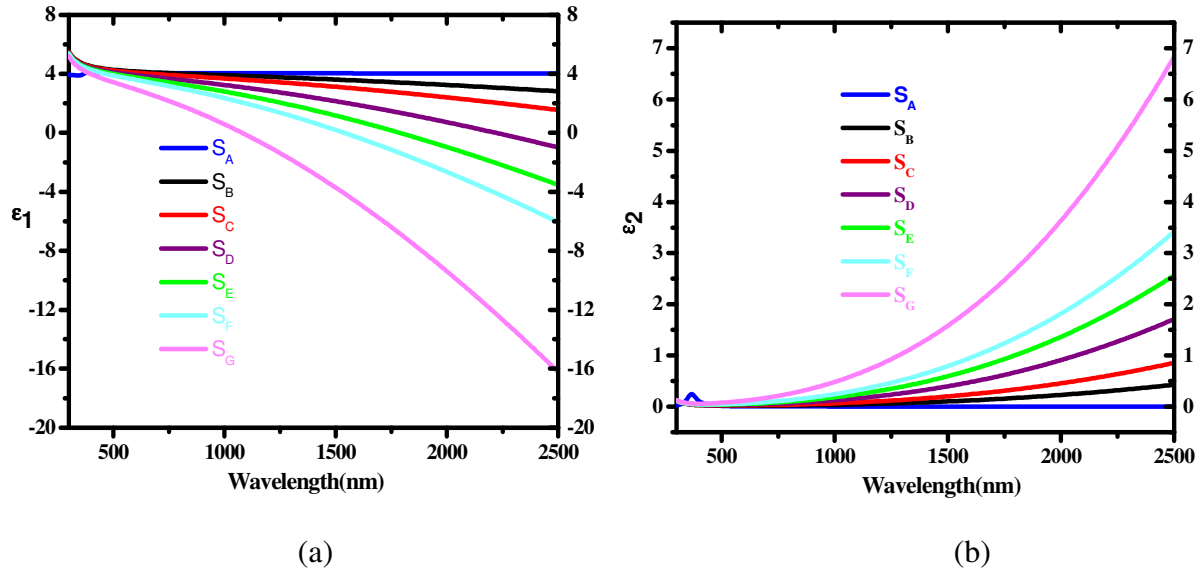


Figure 4. The real part of dielectric constant, ϵ_1 and the complex dielectric constant, ϵ_2 verses wavelength.

It can be concluded from the study of optical constants that in practice it is only ϵ_1 which can be negative.

Table 3: Carrier concentration, n_e values at different plasma frequencies for the samples at $d = 350\text{nm}$

Sample	Plasma frequency, ω_p ($\times 10^{15} \text{s}^{-1}$)	Plasma wavelength, λ_p (nm)	Carrier concentration, ($\times 10^{20} \text{cm}^{-3}$)
S_D	0.81916	2301.08	1.6817
S_E	1.0422	1808.60	2.7223
S_F	1.2354	1525.81	3.8249
S_G	1.7870	1054.84	8.0029

Table 4: Carrier concentration, n_e values at different film thickness.

Thickness d(nm)	Sample	Plasma frequency, ω_p ($\times 10^{15} \text{ s}^{-1}$)	Plasma wavelength, λ_p (nm)	Carrier concentration, ($\times 10^{20} \text{ cm}^{-3}$)
100	S _D	1.3043	1445.16	4.2637
200	S _E	1.6905	1115.05	7.1619
350	S _F	1.7870	1054.84	8.0029
600	S _G	1.8166	1037.63	8.2705

Using values in tables 3 and 4 we drew the graphs of carrier concentration, n_e as a function of plasma frequency, ω_p . The graphs are as shown in figures 5. It was clearly noted from the figures that the carrier concentration of all the samples increases linearly with increasing plasma frequency, ω_p . This further makes it clear that it is the carrier concentration that shifts the plasma edges towards the visible range as was shown in figures 1.

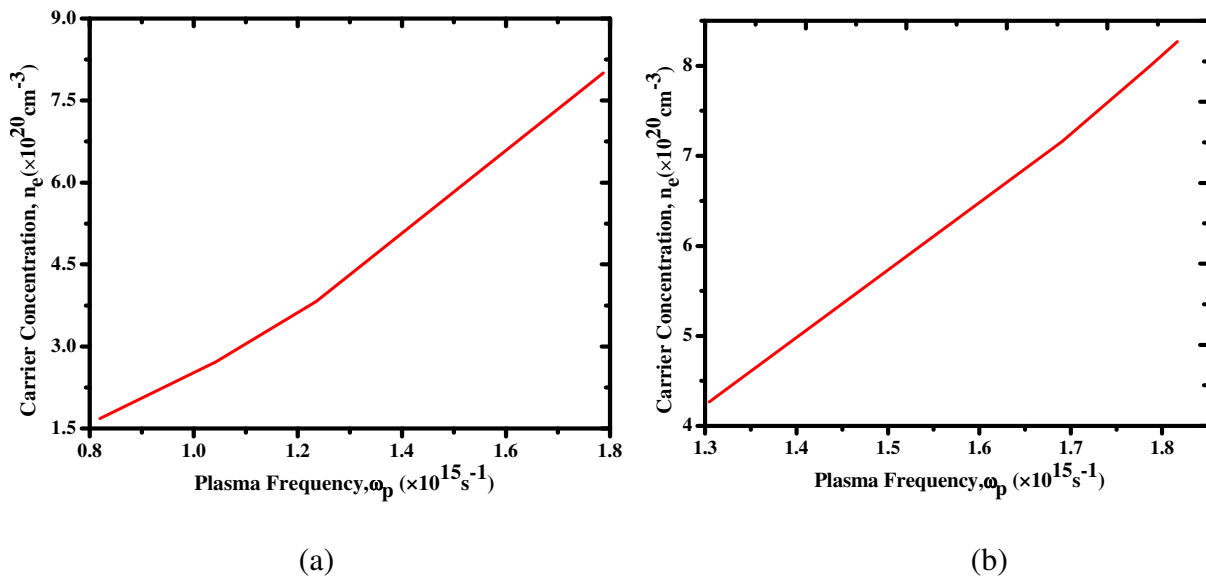


Figure 5. Carrier concentration against wavelength showing (a) various plasma frequencies of the samples and (b) various film thicknesses of the samples.

The optical band gap E_g was evaluated from the standard expression[36].

$$\alpha h \nu \propto (h \nu - E_g)^n \tag{25}$$

where h is Planck's constant, ν is the frequency and hence $h\nu$ is the photon energy in electron volts (eV) and $\alpha = \frac{2\pi k}{\lambda}$ is the absorption coefficient. The constant n depends on the optical transition mode having the values as listed in Table 4.

The Plots of $(\alpha h\nu)^{\frac{1}{2}}$ versus photon energy, $h\nu$, in the high absorption region, and extrapolation of the curve to $h\nu$ axis gives the indirect band gap. Similarly, $(\alpha h\nu)^2$ versus $h\nu$ and extrapolating to the $h\nu$ axis gives direct band gap. Tin oxide is a direct band gap material [37].

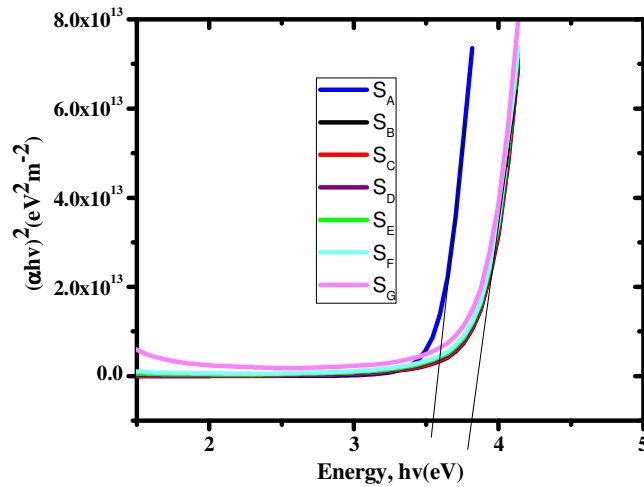


Figure 6. $(\alpha h\nu)^2$ Verses $h\nu$ plots for determining the optical direct band gap of SnO₂ and SnO₂: F.

Figure 6 shows plots of $(\alpha h\nu)^2$ versus photon energy, $h\nu$ in high absorption region. Extrapolation of the curves to $h\nu = 0$ gave the direct band of SnO₂ and SnO₂: Ffilms in the range 3.55eV – 3.81eV for the undoped and heavily doped films. We found out that the direct band gap for SnO₂ to be 3.55 eV which compares well with 3.6eV as already reported[38].

Further, it was noted that there is a widening of band gap with increase of fluorine doping concentration. This widening of the band gap can be understood on the basis of Burstein–Moss shift, which occurs due to filling up of low-lying energy levels by the conduction electrons[39]. According to this well-known Burstein-Moss (BM) shift, above the Mott critical density the partial filling of the conduction band causes a blocking of the lowest states and thus a widening of the optically observed bandgap. Further, above the Mott critical density, the valence and conduction bands are shifted in energy as a result of electron-electron and electron-impurity scattering[22]. In SnO₂ these incline to partially compensate the BM shift.

Now, assuming the function of electron-electron and electron-impurity scattering, the energy gap for direct transitions in the doped material is given in terms of the unperturbed bands as shown in equation 26[22].

$$E_g^o = E_c^o(k_F) - E_v^o(k_F) \quad [26]$$

Alternatively, equation (26) may be expressed as shown in equation (27)

$$E_g^o = E_{g0} + \Delta E_g^{BM} \quad [27]$$

where the BM shift is given by equation (28)

$$\Delta E_g^{BM} = \frac{\hbar^2}{2m_{vc}^*} (3\pi^2 n_e)^{2/3} \quad [28]$$

with the reduced effective mass according to equation (29)

$$\frac{1}{m_{vc}^*} = \frac{1}{m_v^*} + \frac{1}{m_c^*} \quad [29]$$

Equation (29) predicts an energy gap shift proportional to $n_e^{2/3}$. Using equation (28) we calculated the values of BM of the samples S_D, S_E, S_F and S_G. The computed values were 2.7736 × 10¹⁸ eV, 3.8238 × 10¹⁸ eV, 4.7968 × 10¹⁸ eV and 7.8470 × 10¹⁸ eV respectively. From the values it was clear that the optical bandgap should increase.

Table 4: Values of the exponent n for Equation 25 for different band gap transition modes.

	Transition mode
1/2	Direct allowed
3/2	Direct forbidden
2	Indirect allowed
3	Indirect forbidden

Figure 7 shows absorption spectra over the wavelength range 300 – 2500nm for the samples in figure 1(c). The absorption for each sample was calculated from the relation in equation (30). It was noted that almost all the samples have an absorption peak which shifts towards the visible range with increase in fluorine doping concentration. The shift of the position of the absorption edge can be associated to the varying bandgap.

$$T + R + A = 1 \quad [30]$$

where T is the transmittance, R is the reflectance and A is the absorption.

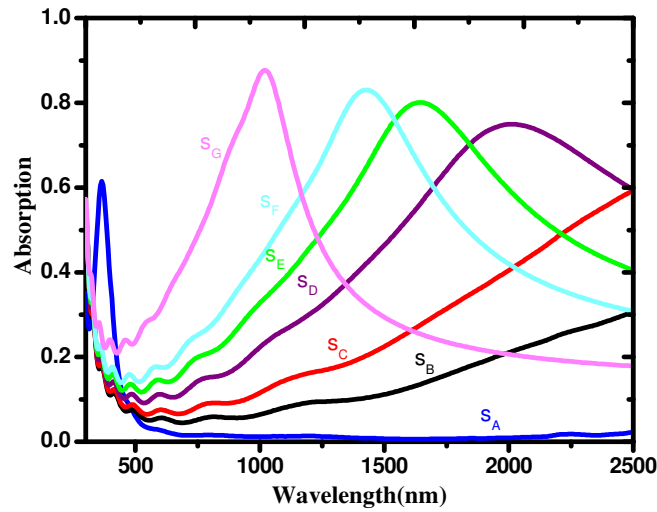


Figure 7. Spectral absorptance $A = 1-(R+T)$ for the samples in figure 1.0 (c).

3.2 Electrical Studies.

The relationship between optical conductivity and the optical constants is as given in equation (31)[34].

$$\frac{\sigma_1}{c} = \frac{nk}{\lambda_0} \tag{31}$$

where $\lambda_0 = \frac{2\pi c}{\omega_0} = 12,850\text{nm}$.

Using the relation in equation (31) we computed the optical conductivity, σ_1 for all the samples and presented the results as shown in figure 8. It was observed from the figure that the optical conductivity increases exponentially with increasing dopant concentration. This effect illustrates that doping improves the conductivity properties of the material to a significant degree.

From figures 4(b) and 8 it is clearly observed that there is a close relationship between the optical conductivity, σ_1 and the imaginary part of the dielectric constant, ϵ_2 .

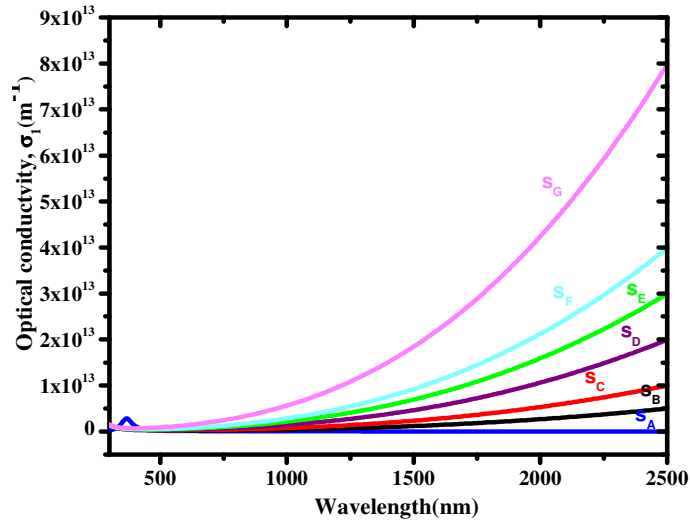


Figure 8 Optical conductivity spectra

4. Conclusion

In this work, fluorine doped tin oxide films were modeled successfully using a dielectric constant of a combined Drude and Lorentz model. From the analysis it was shown that the films had very high visual transmittance and high infrared reflectance. The results implied the possibility of the films to be employed as spectrally selective coating materials. From the analysis it can be concluded that an increase in the doping concentration improves the optical and electrical properties of tin oxide to a greater extent. From the study it can also be concluded that the film thickness also affects the transmittance and reflectance properties of the films. An increase in film thickness leads to an increase in reflectance and a decrease in transmittance.

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References

- [1] C. Granqvist and A. Hultåker, "Transparent and Conducting ITO Films: New Development and Applications," pp. 1-5, 2002.
- [2] Hecht, D. Hu and G. Irvin, "Emerging Transparent Electrodes Based on Thin Films of Carbon Nanotubes, Graphene and Metallic Nanostructures," *Advanced materials*, pp. 1482-1513, 2011.
- [3] B.-Y. & Jeong, M.-C. & Moon, T.-H. & Lee, W. & Myoung, J.-M. & Hwang, Jeoung-Yeon, Seo and Dae-Shik., "Transparent conductive Al-doped ZnO films for liquid crystal



- displays.," *Journal of Applied Physics*, no. 99, pp. 124505-124505., 2006.
- [4] Weis and Martin., "Transparent Electrodes for Flexible Organic Light-Emitting Diodes and Displays.," *Display and Imaging.*, pp. 46-68, 2015.
- [5] P. K. Biswas, "Study of solar radiation at various incident angles on soft chemistry based transparent conducting oxide (TCO) coated window glass," *Journal of Fundamentals of Renewable Energy and Applications*, pp. 57-65, 2018.
- [6] L. E. Runnerstrom, A. Llorde, D. S. Lounisac and J. D. Milliron, "Nanostructured electrochromic smart windows: traditional materials and NIR-selective plasmonic nanocrystals," *Royal society of chemistry*, pp. 10555-10572, 2014.
- [7] S. Boscarino, I. Crupi, S. Mirabella, F. Simone and A. Terassi, "TCO/Ag/TCO transparent electrodes for solar cells application," *Applied Science A*, p. 1287–1291, 2014.
- [8] K. Angelov, H. Komitov and A. Mustafov, "Transparent conductive oxides and their shielding efficiency against electromagnetic interferences," pp. 111-115, 2015.
- [9] B. Karmakar, *Functional Glasses and Glass-Ceramics*, United Kingdom: Butterworth-Heinemann, 2017.
- [10] 24 July 2019. [Online]. Available: https://en.wikipedia.org/wiki/Electrochemical_cell.
- [11] Y.-S. Shim, H. G. Moon, D. H. Kim, H. W. Jang, C.-Y. Kang, Y. S. Yoon and Soek-JinYoon, "Transparent conducting oxide electrodes for novel metal oxide gas sensors," *Elsevier, Sensors and Actuators B*, pp. 357-363, 2011.
- [12] R. Mishra, K. Sheo and S. Prakash, "Optical and gas sensing characteristics of tin oxide nano-crystalline film," *Journal of Ovonic Research*, pp. 77-85, 2009.
- [13] Shamala, Murthy and Narasimha, "Studies on Tin oxide Films Prepared by Electron Beam Evaporation and Spray Pyrolysis Methods," *Indian Academy of Sciences, Bull. Material Sci.*, pp. 295-301, 2004.
- [14] Chitra, Takwale, Bhide, Shailaja and Kulkarni, "Effect of Sn incorporation on the growth mechanism of sprayed SnO₂ films.," *American Institute of Physics*, pp. 73-82, 1991.
- [15] Z. Shanting, "Study of fluorine-doped tin oxide (FTO) thin films for photovoltaics applications," *Materials Universite Grenoble*, p. 40, 2017.
- [16] Z. Wang, C. Chen, K. Wu, H. Chong and H. Ye, "Transparent conductive oxides and their applications in near infrared Plasmonics," 2019.
- [17] G. Roy, "Criteria for choosing Transparent conductors," *MRS Bulletin*, pp. 52-57, 2000.
- [18] G. Dobrikov, M. Rassovska, N. Andreev, S. Boyadzhiev, K. Gesheva, T. Ivanova, P. Sharlandjiev and D. Nazarowa, "Development of transparent heat mirrors based on metal



- oxide thin film structures," *Thin Solid Films*, pp. 1091-1094, 2009.
- [19] R. W. Ronard, "Thin-film Coatings: Understanding key design principles of antireflection coatings," *Laser Focus World*, 2016.
- [20] A. Thelen, "Energy Related Optical coatings," *Optical coating laboratory*, pp. 65-80, 1981.
- [21] K. Nakataa and A. Fujishima, "TiO₂ photocatalysis: Design and applications," *Journal of Photochemistry and photobiology C*, pp. 169-189, 2012.
- [22] H. Ivar, "Indium-Tin-Oxide Thin Films: Basic Optical Properties and applications to Energy Efficient Windows," Chalmers University of Technology, Goteborg, Sweden, 1984.
- [23] C. Maghanga, *Preparation and Characterisation of a Spectrally Selective Reflector Surface Based on TiO₂:Nb Thin Films.*, Eldoret: Moi University, 2009.
- [24] J. (. Wanga and D. Shi, "Spectral selective and photothermal nano structured thin films for energy efficient windows," *Applied Energy* 208, pp. 83-96, 2017.
- [25] F. Mark, *Optical Properties of Solids*, New York: Oxford University Press, 2001.
- [26] C. G. Ribbing, *Introduction to Material Optics, a Compendium*, Sweden: Uppsala University, 2002.
- [27] S. JI and R. NAB, "Effect of Processing on the Electrical Properties of Spray-Deposited SnO₂:F Thin Films.," *Journal of Applied Science*, pp. 672-677, 2008.
- [28] R. Swinepoxes, "Determination of Thickness and Optical Constants of Amorphous Silicon," *Journal of Physics*, p. 1214, 1983.
- [29] W. Theiss and W. Teiss(Ed.), "Scout Thin film Analysis Software Handbook, Hard and Software," *Aachen, Germany*, pp. 54-57, 2001.
- [30] J. S. Maudes and T. Rodrigues, "Sprayed SnO₂ films: Growth Mechanism and film Structure Characterization," *Thin film solids*, pp. 183-189, 1980.
- [31] M. J. Mageto, C. Maghanga, M. Mwaburi and H. Jafri, "Transparent and conducting TiO₂:Nb thin films prepared by spray pyrolysis technique," *American Research Journal of Physics*, p. 63, 2015.
- [32] D. Mergel and Z. Qiao, "Dielectric modelling of the optical spectra of thin In₂O₃:Sn films," *Journal of Physics D: Applied Physics*, pp. 794-801, 2002.
- [33] M. J. Mageto, C. Maghanga and M. Mwamburi, "The Lorentz Oscillator Model simulation Illustrating a Broad Maximum in the Bulk Reflectance for Frequencies Just Above the Resonance Frequency," *The African Review of Physics*, pp. 95-105, 2012.
- [34] F. Wooten, *Optical Properties of Solids*, New York: Academic Press, 1972.



- [35] W. Q. Hong, "Extraction of extinction coefficient of weak absorbing thin films from special absorption," *Journal of Applied Physics D: Applied Physics*, vol. 22, pp. 1384-1385, 1989.
- [36] C. Granqvist, *Handbook of Inorganic Electrochromic Materials*, the Netherlands: Elsevier, Amsterdam, 1995, pp. 265-275.
- [37] E. Shanthi, V. Dutta, A. Banerjee and K. Chopra, "Electrical and Optical Properties of undoped and antimony-doped tin oxide films," *Journal of Applied Science*, pp. 6243-6253, 1980.
- [38] S. Zhang, "Study of fluorine-doped tin oxide (FTO) thin films for photovoltaics applications," *Materials Universite Grenoble Alpes*, 2017.
- [39] I. Hamberg and C. Granqvist, *Appl. Phys.*
- [40] Granqvist, private communication: E-beam evaporated ITO is produced commercially by OCLI, California, 1984.