European Journal of
Technology
(EJT)

Investigation of IR Reflective Coating for Plexiglas Canopy

Sara Perjalian

European Journal of Technology
ISSN 2520-0712 (online)
Vol.7, Issue 2, pp 50 - 68, 2023
www.ajpojournals.org

Investigation of IR Reflective Coating for Plexiglas Canopy

Sara Perjalian[1*]

[1]Faculty of Applied Science Electrical Engineering, Nanotechnology and Microsystems, University of British Columbia

Article history

Submitted 28.04.2023 Revised Version Received 11.07.2023 Accepted 16.07.2023

Abstract

Purpose: Solar energy is necessary for our global ecosystem. In certain times and parts of the world, the heat generated from the energy of the Sun becomes uncomfortable for us and we need to use additional energy to cool down the generated heat from the Sun. This additional energy usage is detrimental to our environment due to generation of air pollution and use of our natural energy resources. The purpose of this paper is to investigate prevention of undesired generation of heat by the Sun using reflective coating materials.

Methodology: In this study, using literature review, Ga doped Zinc Oxide (GZO) is theoretically investigated as a visible light transparent and infrared reflective coating material for the Plexiglas canopy of a solar car. The effect of doping concentration and film thickness is reviewed and discussed. Indium Tin Oxide (ITO) is also studied, using various literature reviews, as an infrared reflective coating material that is transparent in the visible light region. Finally, a spectrophotometer was used to examine the optical properties of a Plexiglas, slide glass, and ITO coated glass, and the results of UV and visible light transmittance measurement of the three materials is presented and discussed.

Findings: GZO and ITO films both have high transparency in the visible region of the solar spectrum and high reflectivity to IR radiation starting from 1500 nm to higher wavelengths. None of these films completely reflect the IR radiation with wavelengths in the range of 700 nm to 1500 nm which contribute to generation of heat most. Many factors such as doping concentration and thickness of the films affect reflectivity of the films due to their effect on shifting the plasma frequency. Increasing doping concentration and thickness of the GZO films until a certain threshold improves IR reflectivity of GZO films, but it was not possible to precisely formulate these factors within this study. Reducing the particle size in nanoparticle ITO film improves transmittance of the film in the visible light region and its reflectance in the IR region. The measurement results showed that Plexiglas and glass have a high transparency to visible and near IR radiation.

Recommendations: Further investigation and experimentation is recommended to fully understand and formulate doping concentration and film thickness of GZO and ITO to achieve optimal IR reflectivity within the 700 to 1500 nm wavelength region while maintaining visible light transparency. In regards to ITO coating, reduced nanoparticle size is recommended to improve the desired visible and IR transparency and reflectivity of the film. Although GZO and ITO coatings' doping concentration and thickness to achieve IR reflectivity within the 700 to 1500 nm wavelengths is not well understood in this study, to reduce heat generation they are still recommended as a coating material due to their reflectivity to IR with wavelengths of above 1500 nm which also play a role in generation of heat.

Keywords: *Nanotechnology, GZO Coating, ITO Coating, Ga Doped Zinc Oxide, Indium Tin Oxide, Infrared Reflectivity*

1.0 INTRODUCTION

A large portion of the solar spectrum is absorbed or reflected by the atmosphere and only wavelengths from 295 to 2500 nm are transmitted and reach the surface of the Earth. This transmitted portion is divided into three main categories. Radiations with wavelengths in the range of 295 to 400 nm have high energy and are called ultraviolet, wavelengths between 400 and 700 nm are visible light, and wavelengths above 700 nm are infrared radiation which are responsible for heating up objects since the energy from infrared radiation causes molecular vibration in objects [1]. Eliminating absorption or transmission of the IR portion of the solar spectrum by material, therefore reduces temperature increase.

Statement of Problem

The focus of this project is to research and investigate an IR reflective coating material for the surface of the canopy of a solar car. The coating needs to be transparent to the visible light. The advantages of IR reflective coatings are the reduction of heat transferred into the car resulting in the comfort of passengers, reduction of energy required for air conditioning, reduction of air pollution from the usage of energy, and an increase of material durability due to less thermal degradation [1]. In this report, I present an in depth theoretical investigation of Ga doped Zinc Oxide (Ga:ZnO) (GZO) as a possible solution for this project. I also present some research on Indium Tin Oxide (ITO) as another choice for coating material. The canopy of the solar car is made of Plexiglas which acts as the substrate for deposition of the coating material. Therefore, I investigate the optical properties of Plexiglas to find its limitations or advantages and determine if it needs coating for IR reflection. Finally, I present the results of transmittance measurements of Plexiglas, slide glass, and ITO coating in the UV-VIS range.

2.0 LITERATURE REVIEW

Theoretical Analysis of Material

In the following sections, theoretical analysis of optical properties of possible coating materials and the Plexiglas substrate is presented based on literature review.

Coating Material: GZO

Previously, research on transparent conducting oxide (TCO) thin films focused widely on fluorine tin oxide (FTO) and indium tin oxide. However, a lot of attention is recently towards zinc oxide (ZnO) based thin films due to advantages of non-toxicity, chemical and thermal stability, and lower cost and availability since zinc is approximately 1000 times more abundant than indium [2]. ZnO has a direct large band gap of 3.4 eV, which makes it a good candidate for optical applications. Non-doped ZnO has high electrical resistivity. Doping ZnO with Ga and Al not only shows increase in electrical conductivity but also it shows high reflectivity in the infrared radiation region because of the resonance plasma effect induced by increased carrier density [2], [3]. Using Al as dopant is low cost, but Al is highly reactive which can be problematic for film growth. Although doping with Ga is more expensive, it is less reactive and was shown to have higher transmittance in the visible region of the solar spectrum [2], [4] which makes gallium doped zinc oxide a promising candidate for this project.

European Journal of Technology
ISSN 2520-0712 (online)
Vol.7, Issue 2, pp 50 - 68, 2023
www.ajpojournals.org

Optical Characteristic of GZO and Relation to Ga Doping Concentration

Figure 1 shows the UV-VIS-NIR transmittance and reflectance of GZO film with different Ga doping concentrations deposited on a glass substrate to study the effect of different concentrations of Ga doping on electrical and optical properties of the film [3].

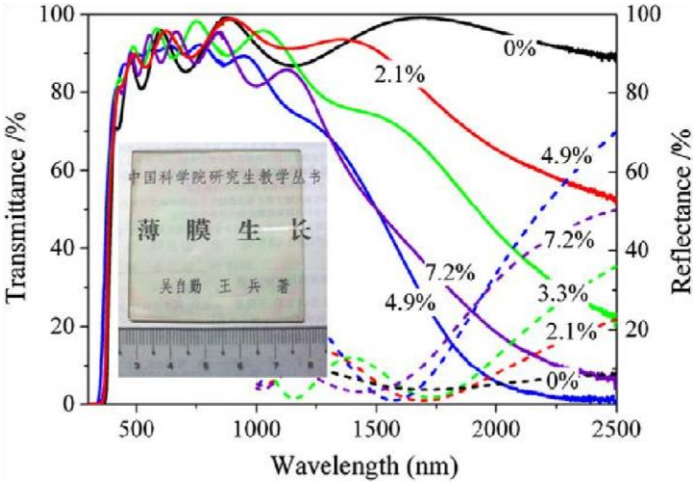


Figure 1: Transmittance and Reflectance Spectra of GZO Films with Different Ga Doping Concentration (At. %) on Glass Substrate [3]

The average transmittance of the visible light with wavelengths of 400 to 800 nm was measured to be about 90%, excluding the effect of the glass substrate [3]. We can see from the graph that non-doped ZnO has high transparency in the NIR region, but transmittance decreases and reflectance increases in the NIR region with increasing the Ga doping concentration. At the point where the wavelength is about 2500 nm, GZO film with 4.9 at. % of Ga doping concentration shows the lowest transparency of less than 1% and highest reflectivity of above 70% [3]. This graph shows that increasing Ga doping concentration does not change transmittance in the visible region significantly, and the most prominent effect of increasing Ga doping concentration is on increasing the reflectivity in the infrared region. This is a promising result, since a large portion of IR radiation is reflected which has a large effect on resisting the temperature rise due to IR radiation. This point with a wavelength of 2500 nm determines the resonance plasma frequency, ω_p [3].

Plasma frequency has an important role in optical properties of material. Light with frequency lower than the plasma frequency is reflected, since electrons in the material screen the electric field component of the light. However, if the frequency of the light is above the plasma frequency of the material, it is transmitted since the electrons are not able to respond fast enough to screen the electric field of the light [5]. So, Photons with energy $\hbar\omega < \hbar\omega_p$ are reflected, where $\hbar$ is the reduced Plank's* constant and ω is the frequency of a photon [3]. According to Drude theory, ω_p can be defined through following equation [3]:

$$\omega_{p2} = n_e e_2 / \varepsilon_0 \varepsilon_\infty m_{e*} - \gamma_2 \quad (1)$$

$$\gamma = e / (m_e \mu) \quad (2)$$

where n_e is the free electron concentration, m_e is the effective mass of the electron, ε_0 is the permittivity of free space, ε_∞ is the high frequency dielectric constant, and μ is the electron mobility. And normally $\omega_p >> \gamma$ [3], therefore:

$$\omega_{p2} \sim n_e e_2 / \varepsilon_0 \varepsilon_\infty m_{e*} \quad (3)$$

The wavelength corresponding to resonance plasma frequency is thus [3]:

$$\lambda_p = 2\pi c_0 / \omega_p \quad (4)$$

where c_0 is the speed of light in free space.

Therefore, we can shift the point where we want the transmittance stop and reflectivity start to shorter wavelengths in order to achieve higher IR reflectivity by choosing the wavelength and finding ω_p in equation (4), and then substituting ω_p in equation (3) to find the required carrier concentration. We can see in equation (3) and (4) that we can shift λ_p to shorter wavelengths corresponding to higher frequencies by increasing carrier concentration. Therefore, higher Ga doping concentration has better IR reflectivity [3].

Figure 2 shows the dependence of carrier concentration on transmittance and reflectance of GZO film at 2500 nm wavelength. This graph agrees with the theoretical analysis and shows a decrease in transmittance and an increase in reflectance as carrier concentration increases. The authors state that Ga doping concentration of ~4.9 at. % has the carrier concentration of $1.7u10^{21}$ cm^{-3} which shows the highest reflectance of above 70% [3].

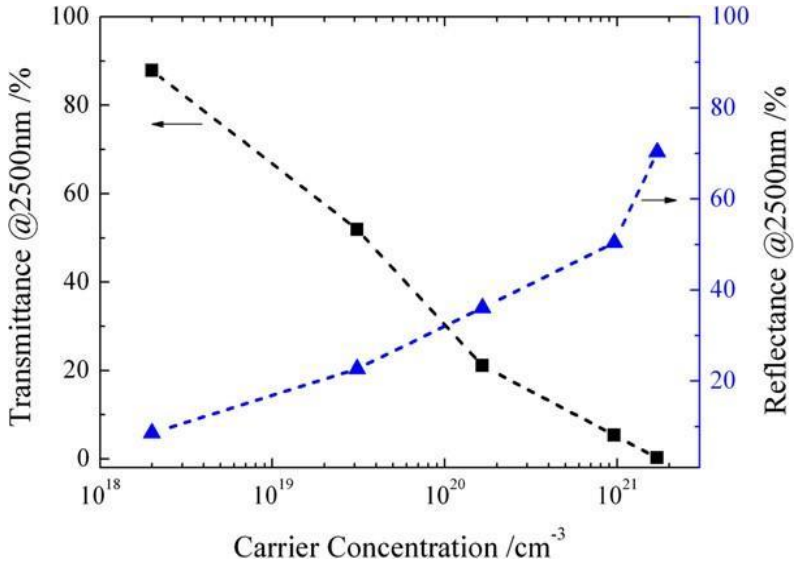


Figure 2: Transmittance and Reflectance Dependency to Carrier Concentration in GZO Film at Wavelength of 2500 Nm [3]

So, to design and predict the optical properties of GZO thin film I would use equation (3); in this equation, however, it is not stated in the article [3] that what values are used for ε_∞ and m_e for GZO film. Therefore, I would use the data at 4.9 at. % Ga doping content corresponding to

European Journal of Technology
ISSN 2520-0712 (online)
Vol.7, Issue 2, pp 50 - 68, 2023
www.ajpojournals.org

carrier concentration of $1.7u10^{21}$ cm^{-3} at 2500 nm wavelength to reverse engineer and find out what value they used for the combination of $e^2/ \varepsilon_0 \varepsilon_\infty m_e$.

$\lambda_p = 2\pi c_0 / \omega_p$ and λ_p= 2500 nm → ω_p= $7.51u10^{14}$ rad/sec $\omega_p^2 \sim n_e e^2/ \varepsilon_0 \varepsilon_\infty m_e^*$ and n_e= $1.7u10^{21}$ cm^{-3} = $1.7u10^{27}$ m^{-3}

→ $e^2/ \varepsilon_0 \varepsilon_\infty m_e^* \sim \omega_p^2 / n_e$= 332.18

Now I will use this value to theoretically predict what Ga doping concentration we would need to shift the maximum IR reflectance point to 2000 nm.

$\lambda_p = 2\pi c_0 / \omega_p$ at λ_p= 2000 nm → ω_p= $9.39u10^{14}$ rad/sec $\omega_p^2 \sim n_e e^2/ \varepsilon_0 \varepsilon_\infty m_e^*$ → n_e= $2.66u10^{27}$ m^{-3} = $2.66u10^{21}$ cm^{-3}

$\frac{4.9at.\%}{1.7\times 10^{21}\ \ cm-3} = \frac{Ga.Dopping.Concentration}{2.66\times10^{21}\ \ cm-3}$ → Ga doping concentration = 7.67 at.%

Therefore, in theory, Ga doping with concentration of 7.67 at.% will potentially result in complete IR reflectance (reflects λ > 2000 nm). However, this theoretical result does not completely match the results of the measurements in figure 1. For example, the graph of transmittance of GZO with doping concentration of 7.2 at.% does not completely match our theoretical analysis. This suggests that my assumption for the combined value of $e^2/ \varepsilon_0 \varepsilon_\infty m_e$ is not right because the value of ε_∞ and m_e varies with wavelength and carrier concentration respectively, and I cannot simply use the values used for other concentrations and frequencies. Furthermore, it suggests that other factors also affect the reflectivity and transparency cut-off point.

Photon Absorption in Semiconductors

In order to explain the behavior of the GZO's graph for absorption and transmittance of light in UV and visible region, some background information regarding absorption of photon in semiconductors is needed. If an incident photon's energy (E_p) is larger than a semiconductor's band gap (E_g), then that photon can be absorbed by the valence electrons in the valence band of the semiconductor, resulting in transfer of an electron from the valence band to the conduction band. This concept is demonstrated in figure 3 [6].

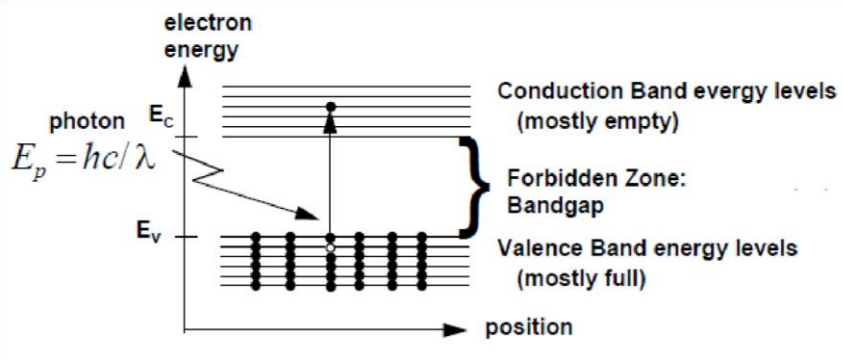


Figure 3: Energy Absorption and Transition of an Electron from Valence to Conduction Band [7]

E_g is the electron required to break a covalent bond in the valence band, and when this energy is provided by absorption of photon's energy, the electron becomes free to transfer to the conduction band and move freely in the crystal lattice. However, if the photon's energy is less than E_g, it cannot promote the electrons from the valence band to the conduction band. Therefore, because an electron cannot exist in the forbidden zone between the bottom of the conduction band and the top of the valence band, the photon is passed through the material without promoting any electron and is transmitted [6].

To approximate the value of the band gap in a semiconductor, we can shine light with different energy (wavelength) on it and measure the point where the absorption stops and transmission starts. This point is called the absorption edge and the energy of photon at this point is corresponding to the band gap of the material [6].

In figure 1 we see that the photons with wavelengths lower than 400 nm (in the UV region) are not transmitted or reflected. We see a sharp absorption edge which indicates the near-band-edge (absorption edge) excitation. These photons have energies higher than the band gap ($\hbar\omega > E_g$) [3].

We can estimate the band gap energy of the GZO film from this point which is located at ~ 300 nm. The following shows the required calculation:

$$f = c_0 / \lambda = \frac{2.9979 \times 10^8}{300 \times 10^{-9}} = 7.99\times 10^{14}\ Hz$$

$$E_g = \hbar\omega = (h/2\pi)(2\pi f) = (6.63 \times 10^{-34}) \times (7.99 \times 10^{14}) = 5.3 \times 10^{-19}\ J$$

$$\rightarrow E_g = 5.3 \times 10^{-19}\ J \times \frac{1eV}{1.6 \times 10^{-19}\ J} = 3.32\ eV$$

So the band gap of the GZO is about 3.32 eV. This value will be confirmed using other methods in the following sections.

Absorption Coefficient and its Relation to the Band Gap

The absorption coefficient of direct band gap semiconductors can be defined by the following equation when receiving high photon energies [3], [6]:

$$\alpha^2 = A\ (E_p - E_g) = A\ (\hbar\omega - E_g) \quad (5)$$

where α is the absorption coefficient and A is a proportionality constant. The

absorption coefficient and the optical band gap of the material can be approximated from its transmittance spectrum by following procedure [3], [7].

According to equation (5) absorption coefficient of the material is given by:

$$\alpha \propto \sqrt{Ep - Eg} \quad (6)$$

Light incident on the film is partially reflected and according to Fresnel power reflection coefficient [7]:

$$R_1 = \left(\frac{n_s - 1}{n_s + 1}\right)^2 \quad (7)$$

where R_1 represents the reflection from the surface of the film. Then the light intensity that is measured just inside the film is given by [7]:

$$I_{s1} = I_0(1 - R_1) \quad (8)$$

where I_0 is the intensity of the light incident on the film. Also, the intensity of the light at the lower end of the film can be defined as [7]:

$$I_{s2} = I_0(1 - R_1)\exp(-\alpha d) \quad (9)$$

Here, d denotes the thickness of the film. Furthermore, we must consider Fresnel reflection at the film-substrate and substrate-air interfaces and also optical scattering denoted by R_2, R_3, and S respectively. Therefore, the percentage of transmittance can be indicated by following equation [7]:

$$T = \left(\frac{I_{transmitted}}{I_0}\right)(1 - R_1)(1 - R_2)(1 - R_3)(1 - S)\exp(-\alpha d) \quad (10)$$

In the above equation the interference and multiple reflection is neglected. The absorption coefficient as a function of photon energy can be defined as [7]:

$$\alpha(E) = -\frac{1}{d}\ln\left(\frac{T(E)}{(1 - R_1)(1 - R_2)(1 - R_3)(1 - S)}\right) \quad (11)$$

Or alternatively, we can define the absorption coefficient as a function of wavelength. We can neglect Fresnel scattering and reflection if we normalize the transmittance data in a way that $T_{normalized}$=100% in the transparent region of the spectrum where $\hbar\omega < E_g$, therefore [7], [6]:

$$\alpha(E) = -\frac{1}{d}\ln(T_{normalized}(E)) \quad (12)$$

So, from the equation (12) we see that if we have the transmittance with respect to wavelength, we can convert the wavelength to its equivalent energy and plot the absorption coefficient with respect to energy. According to equation (5), α^2 has a linear dependency on E. Therefore, we can plot α^2 with respect to E and extrapolate the linear portion of the graph to α=0 and find the value of the band gap energy [7], [6].

Figure 4 shows the graph of α^2 with respect to energy of the incident light and the extrapolation of the linear part to α=0 which estimates the energy of the band gap of the GZO films with different Ga concentration. This graph corresponds to the graph of transmittance and reflectance of GZO films with different concentrations in figure 1 [3]. It can be seen that the band gap of the film with 4.9at.% is about 3.37 eV which is close to the approximation value (3.2 eV) calculated from the transmittance graph in section 2.1.2.

European Journal of Technology
ISSN 2520-0712 (online)
Vol.7, Issue 2, pp 50 - 68, 2023
www.ajpojournals.org

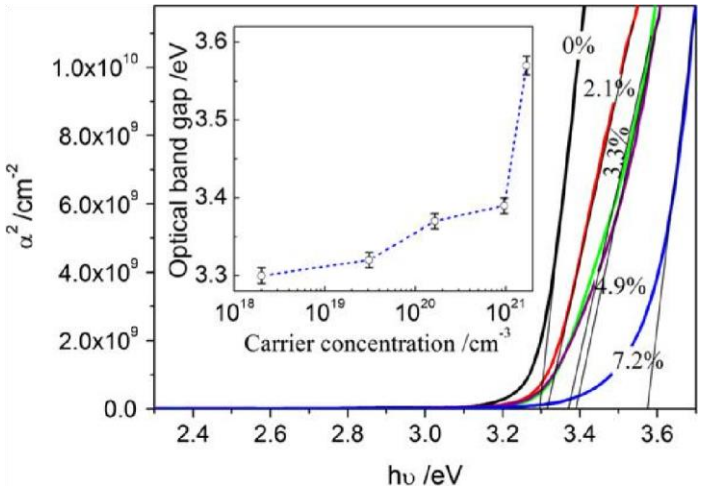


Figure 4: Graph of A^2 Vs. Energy of Wavelength for GZO Films of Different Doping Concentration. The Inner Graph is the Effect of Doping Concentration on Optical Band Gap Derived from Outer Graph [3]

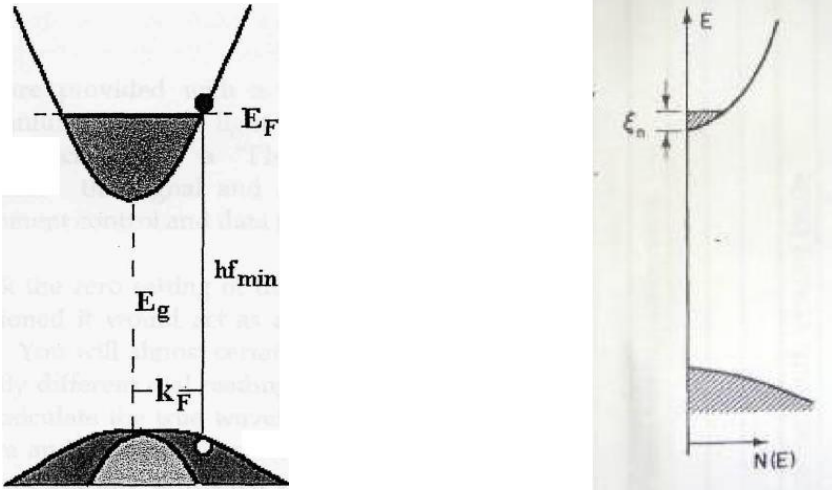


Figure 5: Burstein-Moss Shift in Semiconductors [9]

Effect of Film Thickness on Optical Characteristic of GZO

Another study on GZO thin films shows that their optical properties depend on their thickness. Figure 6 illustrates the optical transmittance of GZO films with various thicknesses deposited onto the sodalime glass substrate using rf magnetron sputtering method [2]. We can see that all of the films with different thicknesses have a high transmittance of between 80 to above 90% in the visible region. However, as the film thickness increases the optical transmittance becomes closer to our desired optical characteristics where the transmittance decreases in the infrared region.

European Journal of Technology
ISSN 2520-0712 (online)
Vol.7, Issue 2, pp 50 - 68, 2023
www.ajpojournals.org

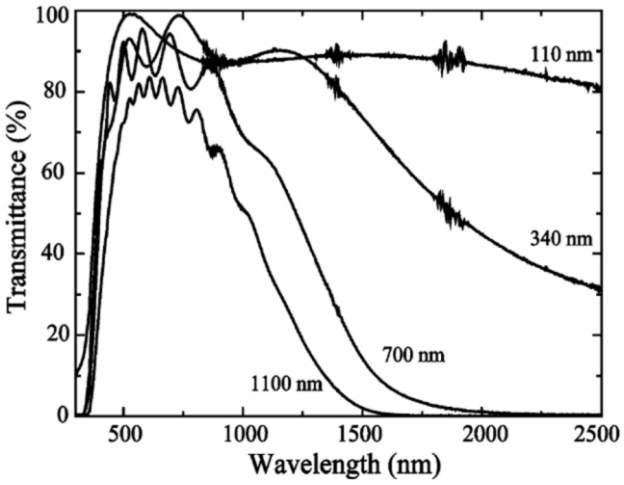


Figure 6: Effect of GZO Film Thickness on Reflectance in IR Region [2]

In this study, the reason for decrease in the transmittance in the near infrared region as the thickness increases is not specifically mentioned, but it is stated that it is consistent with the changes in electrical, morphological, and structural properties [2]. I will analyze these changes to be able to suggest a reason for optical changes. The dependency of electrical resistivity (U), mobility (μ), and carrier concentration (n_e) to the film thickness for GZO films is depicted in figure 7.

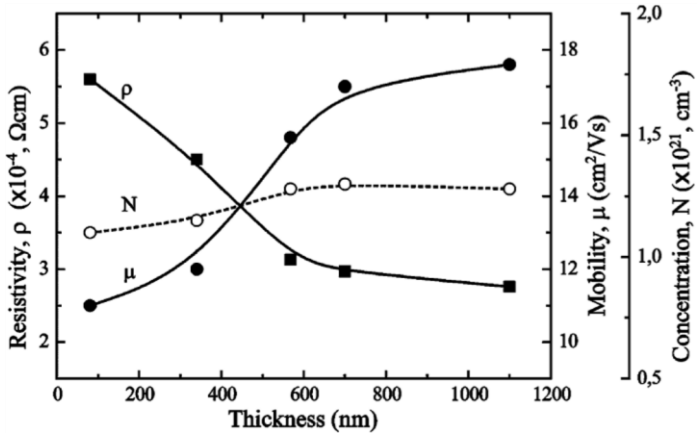


Figure 7: Resistivity, Mobility, and Carrier Concentration Vs. Film Thickness [2]

In the above graph, we see that as the film thickness increases the resistivity decreases, mobility increases, and carrier concentration almost stays the same. The increase in mobility is suggested to be due to the decrease in ionized impurity scattering and increase in the crystallite size in thicker films. It is also stated that thin films have more defects than thick films and this results in more scattering of carriers at intercrystalline boundaries in thinner films, which decreases mobility. The decrease in resistivity is as a result of increase in mobility. In figure 8, the SEM micrographs of surfaces of four GZO films with different thicknesses are shown. We

can see that the surface roughness increases as the thickness increases which corresponds to larger grain sizes in thicker films [2].

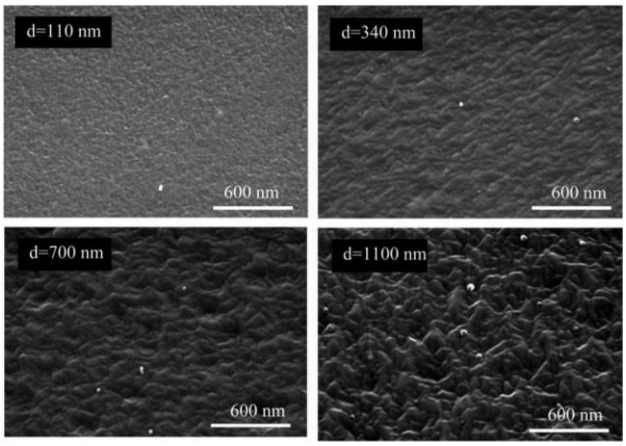


Figure 8: SEM Surface Morphologies of GZO Films with Different Thicknesses [2]

I would suggest the reason for the optical changes is due to the carrier mobility changes. This suggestion is based on the equation (1) and (2) in section 2.1.1. In this section, it is stated that photons with frequencies below the plasma frequency are reflected and the photons with frequencies above the plasma frequency are transmitted.

Note equations (1) and (2) previously mentioned in section 2.1.1:

$$\omega_{p2} = n_e e_2 / \varepsilon_0 \varepsilon_\infty m_{e*} - \gamma_2 \quad (1)$$

$$\gamma = e / (m_e \mu) \quad (2)$$

From equation (2) it is clear that γ decreases as carrier mobility increases. Therefore, plasma frequency in equation (1) increases as γ decreases. So, to reiterate, as the film thickness increases the carrier mobility increases, resulting in an increase in plasma frequency. Consequently, the point at which the transmittance stops shifts to shorter wavelengths, and this results in the behavior of the transmittance graphs in figure 6.

Burstein-Moss Shift in Heavily Doped Semiconductors

It is shown on the graph in figure 4 that the optical band gap increases as doping concentration increases and this is due to the Burstein-Moss shift in semiconductors with high doping concentration [3], [8]. Burstein-Moss shift is a consequence of Pauli Exclusion Principle [9]. When the semiconductor is heavily doped, the states at the bottom of the conduction band will be filled by the carriers and therefore the Fermi level moves up to the inside of the conduction band in n-type semiconductors (figure 5) [9]. As a result, the band gap determined from the measurement of the interband absorption increases by an amount denoted by ξ_n. This concept is demonstrated in figure 5; because the states lower than ξ_n are already populated, transitions of carriers to states lower that $E_g + \xi_n$ are forbidden, resulting in the shift of absorption edge to higher energies by ξ_n [9].

European Journal of Technology
ISSN 2520-0712 (online)
Vol.7, Issue 2, pp 50 - 68, 2023
www.ajpojournals.org

According to a study on the effect of the substrate temperature on the properties of GZO films, temperature increase also causes Burstein-Moss shift [10]. Higher deposition temperature results in higher optical transmittance in the visible region [8]. However, in our project we will not be able to increase the deposition temperature too much because of the low melting point (~160 C) of the Plexiglas substrate.

Analysis of the Refractive Index and Extinction Coefficient of GZO

Figure below depicts the refractive index and extinction coefficient of a 420 nm thick GZO film. The value of the refractive index (n) in the visible region is about 2 [2]. It is shown that the refractive index increases for wavelengths shorter than 400 nm which means the speed of light with short wavelengths (<400 nm) in the film decreases. Extinction coefficient is the imaginary component of the complex refractive index which gives information about absorption of light at different wavelengths [11]. In the graph below, it can be observed that the value of extinction coefficient for wavelengths higher than 400 nm is 0 which means there is no absorption of light in that region. The sharp increase of extinction coefficient for wavelengths below 400 nm indicates a large absorption resulting from the interband absorption [2], which is an indication of the value of the band gap of GZO film using the method described in section 2.1.2.

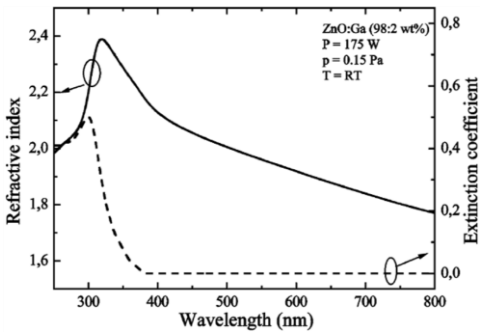


Figure 9: Refractive Index and Extinction Coefficient of a Typical GZO Film with Thickness of 420 Nm [2]

Absorption coefficient is proportionally related to extinction coefficient by the following formula:

$$\alpha = 4\pi k/\lambda \quad (13)$$

where k denotes the extinction coefficient.

Beer-Lambert law relates the intensity of incident light to the intensity of transmitted light, absorption coefficient, and the distance that light travels through the material.

$$I_{transmitted} = I_{incident}\, e^{-\alpha d} \quad (14)$$

This equation is the same as the equation (12) mentioned in the section 2.1.3, in which the term $e^{-\alpha d}$ accounts for decay of light over distance it travels. We can find the skin depth from Beer-Lambert law. Skin depth, denoted by δ, is the depth by which an electromagnetic wave decays

by e^{-1}. In the Beer-Lambert equation, if we equate the term $e^{-\alpha x}$ with e^{-1}, the value of d gives us the skin depth which is the reciprocal of α.

$e_{-\alpha x} = e_{-1}$

$\rightarrow \quad x = \delta = 1/\alpha$ (15)

Coating Material: ITO

Indium Tin Oxide (ITO) films are another candidate for this project. ITO films are highly transparent in the visible region, reflectance in the infrared region, adhesive to the substrate, and electrically conductive. Because of these properties ITO has many applications in transparent electrons in liquid crystal displays, plasma displays, solar cells, and low emissive window glasses. Many methods for synthesizing and processing of ITO films have been researched; however, nanoparticles and quantum dot structures need more research and studies [12]. In this project we are more interested in the optical properties and substrate adhesion of ITO rather than the electrical properties. It is suggested that in nanoparticle ITOs the reduction of the particle size much less than the visible light's wavelength decreases scattering of light significantly, which results in increase of transparency in the visible region [13].

In one study, coprecipitation method was used to produce ITO nanoparticles for preparation of ITO sol solution. The optical properties of the ITO film then were compared to slide glass. Figure 10 shows the result of this comparison in the transmission of near-IR region. Graph A corresponds to slide glass and graph B corresponds to ITO nanoparticle film. As we can see, slide glass is 90% transparent to IR radiation. On the other hand, ITO film is almost 100% reflective to wavelengths above 1500 nm. The ITO film was 390 nm thick and the particle size was measured to be between 15 to 30 nm. This result shows that nanoparticle ITO films are very good IR reflective materials [12].

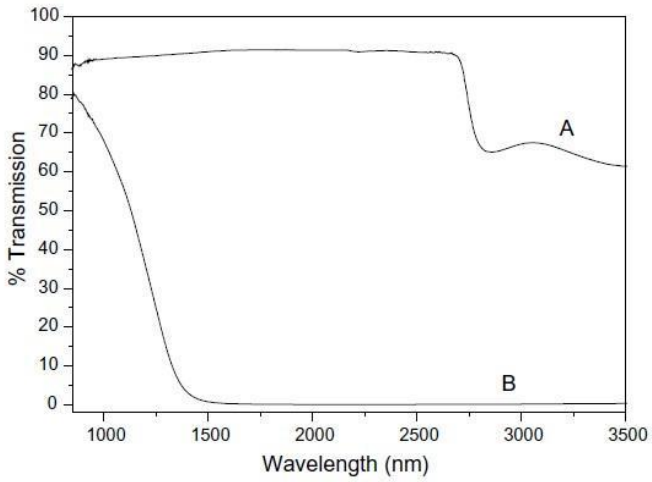


Figure 10: Transmission Spectrum of Slide Glass (A), and ITO Film (B) [12]

It has been observed that in nanoparticle ITO's, the IR reflectance starts in shorter wavelengths compared to regular sized particle ITO's. This means that nanoparticle ITO's reflect more portion of IR radiation resulting in better resistance to heat. I did not find any explanation for this advantage in my literature research. However, I would suggest it is because of the effect of particle size on carrier concentration. When the particle size is very small, carrier concentration may increase, resulting in an increase in plasma frequency explained in section 2.1.1. Therefore, the plasma frequency shifts to shorter wavelengths and IR reflectance starts in shorter wavelengths.

Plexiglas Substrate

In this study, Plexiglas has been chosen as the substrate. Plexiglas is the trademark name for Poly (methyl methacrylate) (PMMA) with chemical formula of $(C_5O_2H_8)_n$, which is a transparent thermoplastic. It is also called acrylic glass [14]. Plexiglas is a material that can be produced in many different colors and has industrial, residential, and commercial applications [15]. It has a melting point of 160 C [14] and because of this low melting point, the methods for deposition of coating material on Plexiglas cannot be high temperature. The refractive index of Plexiglas is 1.4914 at 587.6 nm [14]. Figure 11 depicts the refractive index of Plexiglas versus wavelength [16].

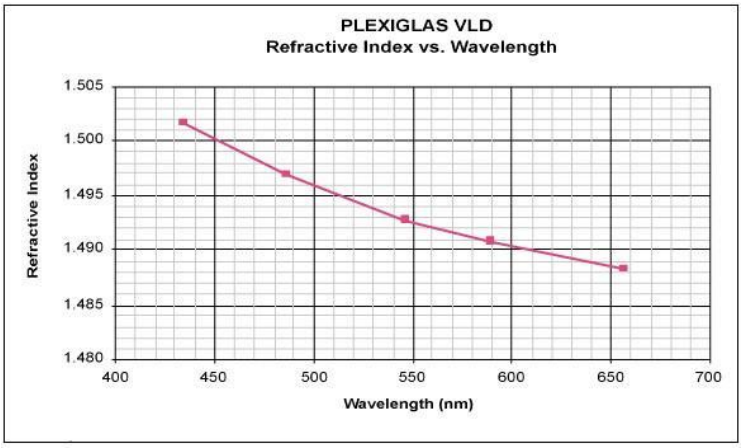


Figure 11: Refractive Index of Plexiglas [16]

Also Figure 12 in the next page shows the graph of extinction coefficient per unit length of Plexiglas compared to polycarbonate in the range of visible light [17]. We know that low extinction coefficient means low absorption of light and therefore high transmittance of light. Extinction coefficient of Plexiglas is very low in the visible region which means it has high transparency in this region.

European Journal of Technology
ISSN 2520-0712 (online)
Vol.7, Issue 2, pp 50 - 68, 2023
www.ajpojournals.org

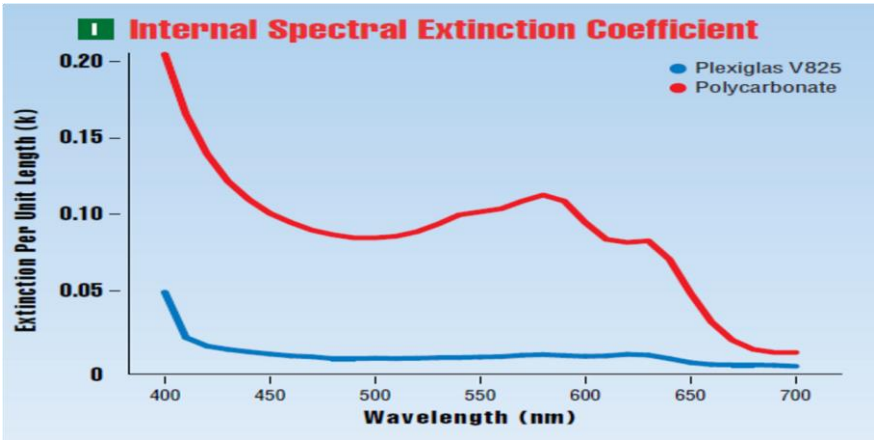


Figure 12: Extinction Coefficient of Plexiglas and Polycarbonate [17]

Optical measurements on colorless Plexiglas with thickness of 6 mm show that it has a transparency of 92% in the visible region. This characteristic makes Plexiglas a perfect transparent medium. Approximately, 8% of the perpendicular light in total is reflected from the front and back surface of the Plexiglas. Transmittance decreases and reflectance increases when the angle of incidence increases. Figure 13 on the next page shows the transmittance of colorless Plexiglas sheets with different thicknesses and formulation modifications in the ultraviolet and visible region [15].

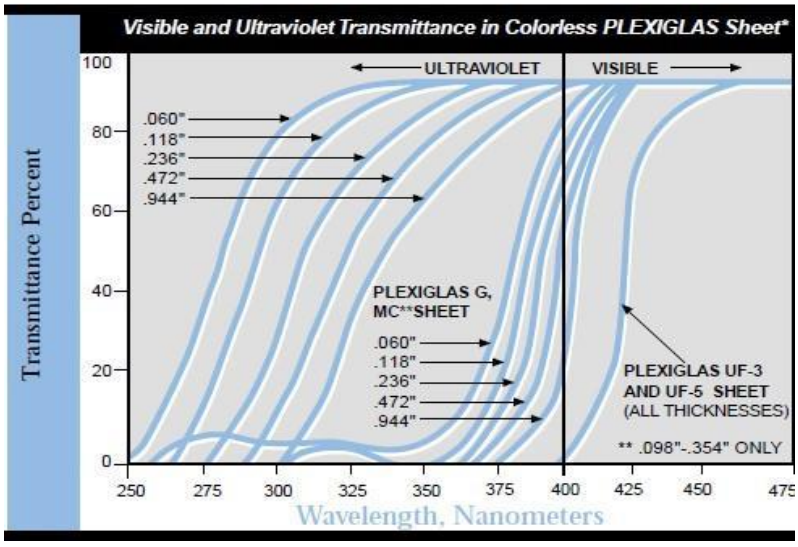


Figure 13: Transmittance of Plexiglas vs. Wavelength [15]

As we can see in the above graph, Plexiglas absorbs UV light with shorter wavelengths while transmitting UV light with longer wavelengths. UV absorbance increases with sunlight exposure for the first two years of exposure and will not change after 5 to 10 years. The UV stability of Plexiglas makes it durable and suitable for prolonged outdoor and artificial light

exposure use. It is also strongly resistant to discoloration for more than 20 years of constant exposure to lit fluorescent lamps [15].

In the near-infrared region, with wavelengths of 700 to 2800 nm, colorless Plexiglas transmits most of the light while absorbing certain bands as depicted in figure 14. These absorption peaks somehow correspond to molecular bond energies. It is also shown in figure 14 that infrared transmittance decreases as the thickness of Plexiglas increases. With thickness of ~ 3 mm (0.118 inch), Plexiglas is completely opaque to wavelengths in the range of 2800 to 25000 nm. If the thickness is less than 3 mm, however, it transmits small portions of radiation energy with certain wavelengths in this region. This range of wavelength is not of our concern anyway because it doesn't contribute to heat generation. Outdoor Exposure to weather does not change the infrared transmittance characteristic of Plexiglas [15].

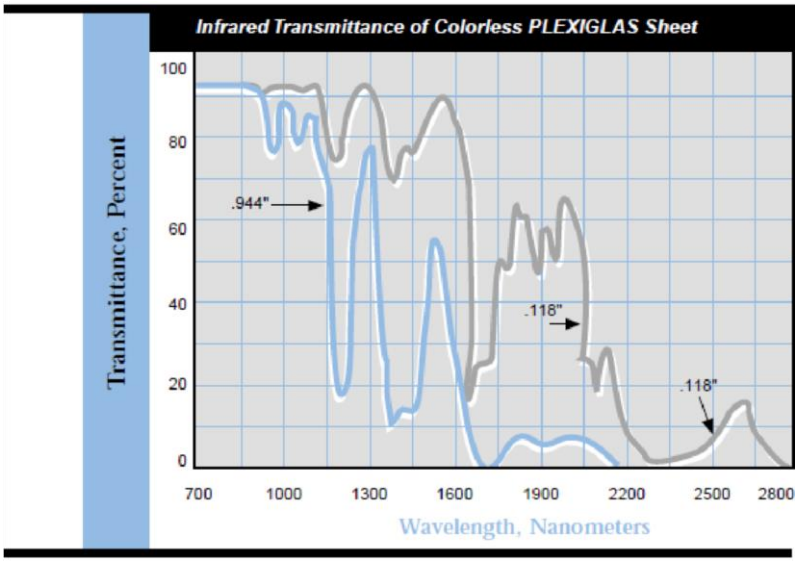


Figure 14: Transmission of Plexiglas with Two Different Thicknesses in Infrared Region [15]

In this section the results of transmittance tests in UV and visible regions are presented. I was not able to test optical properties of GZO because the cost of deposition of GZO using the sputtering method was exceeding the budget for this project.

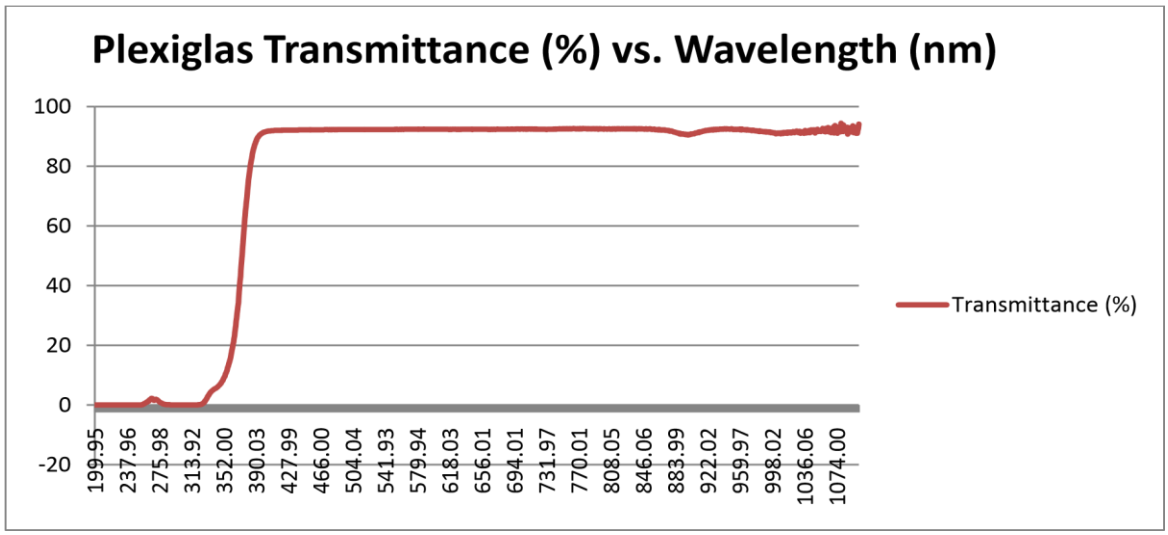
3.0 METHODOLOGY

The tests were done using an spectrophotometer on a piece of Plexiglas, slide glass, and an ITO coated slide glass which were already available in the lab.

4.0 FINDINGS

Figure below shows the test results for transmittance (vertical axis) of Plexiglas versus wavelength of light (horizontal axis). The thickness of Plexiglas is 2.83 mm. As expected, Plexiglas has a transparency of more than 90% in visible and near IR region. For wavelengths

below 380 nm in the ultraviolet region we see a sudden drop of transmittance corresponding to



interband energy absorption.

Figure 15: Transmittance (%) vs. Wavelength (nm) of 2.83 mm Plexiglas

Plexiglas transparency test complies with the theoretical analysis in previous sections. We could not test transparency for above 1100 nm wavelength because our measurement equipment only allows as far as 1100 nm wavelength for tests.

I tried to use the method described in section 2.1.3 to find the band gap of Plexiglas. Below is the graph of α^2 versus energy of the light. But, as it is shown the graph has so much fluctuation at the high energy end and it wasn't possible to extrapolate its linear part to $\alpha=0$. But by looking at it, I estimate the value of the band gap to be about 3.8 eV which is a large band gap suitable for optical applications.

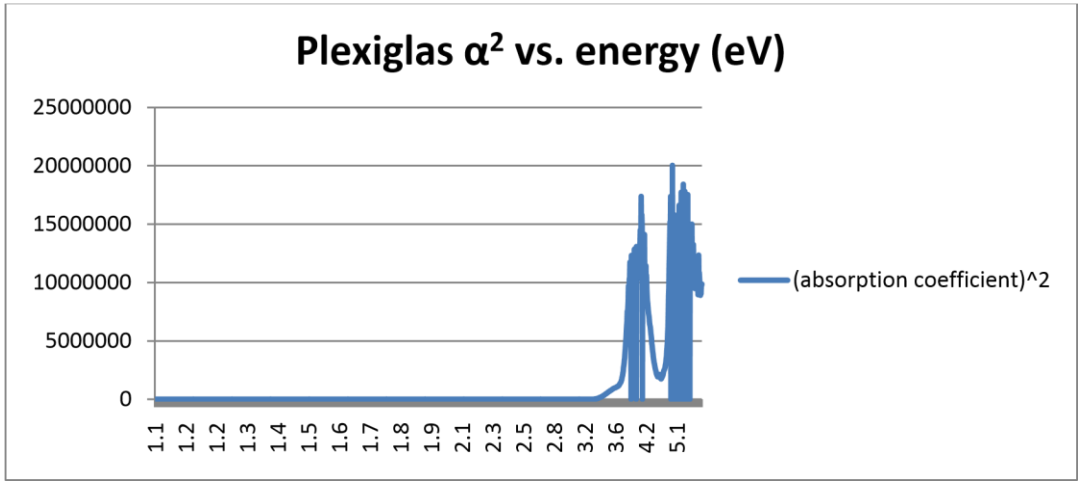


Figure 16: Plexiglas Absorption Coefficient Squared, A^2 (Vertical Axis) Vs. Energy of Light (Ev) (Horizontal Axis)

European Journal of Technology
ISSN 2520-0712 (online)
Vol.7, Issue 2, pp 50 - 68, 2023
www.ajpojournals.org

From theoretical and experimental findings, I conclude that Plexiglas does not reflect near infrared radiation and we need to apply a coating material to Plexiglas surface that reflects infrared to prevent heating.

The second material that we tested was a glass slide. Figure 16 shows the result of transparency test on glass. The thickness of this tested glass is 0.96 mm. As we can see, glass also is above 90% transparent to near infrared, visible, and part of ultraviolet radiation. Therefore, it needs the application of infrared reflective coating material to prevent temperature increase.

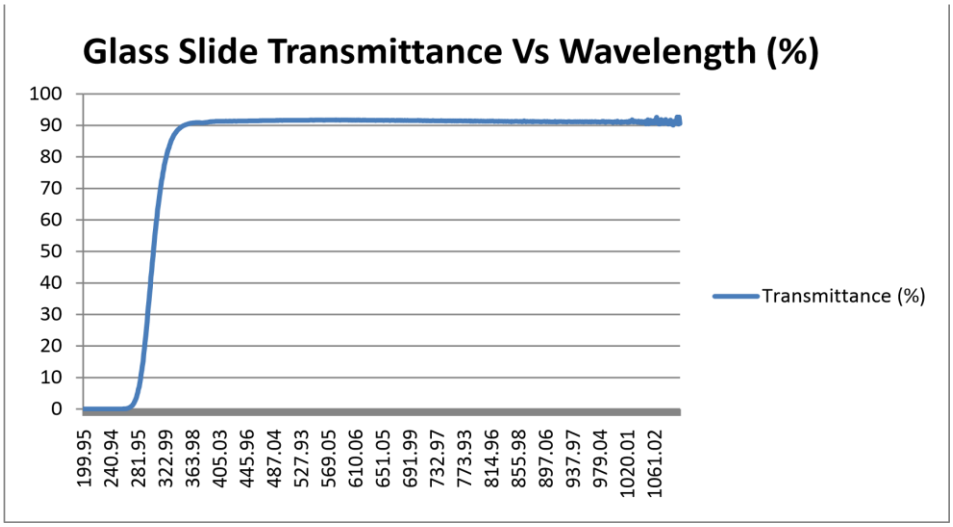


Figure 17: Transmittance (%) vs. Wavelength (nm) of Glass

Plotting the graph of α^2 versus energy in Figure 18, the band gap of the glass seems to be around 4.2 eV which is higher than Plexiglas.

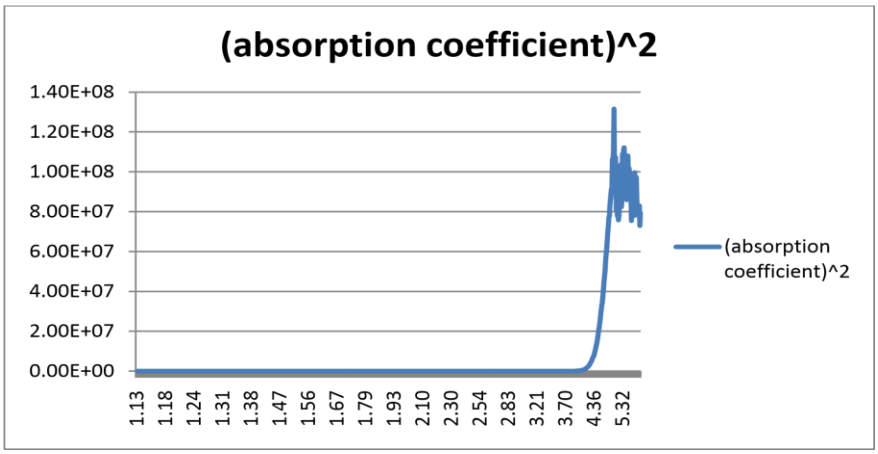


Figure 18: Glass Absorption Coefficient Squared, A2 (Vertical Axis) Vs. Energy of Light (Ev) (Horizontal Axis)

The final tested sample was an ITO coated glass with total thickness of 1.06 mm. Figure 18 shows the transmittance on ITO film excluding the glass substrate. According to this graph,

there is not any significant difference between ITO coated glass and non-coated glass in terms of transparency to different ranges of radiation. However, it seems like there is a measurement error in the graph. I tried to account for the errors and correct them, but still, I get some transmittance values slightly higher than 100%, which is a sign of light amplification or error. The band gap of ITO coating is around the same wavelength as it is in non-coated glass. Based on the data I have from ITO coating; I cannot infer its IR reflecting efficiency because the data doesn't seem to be reliable as it doesn't correspond with theoretical expectation.

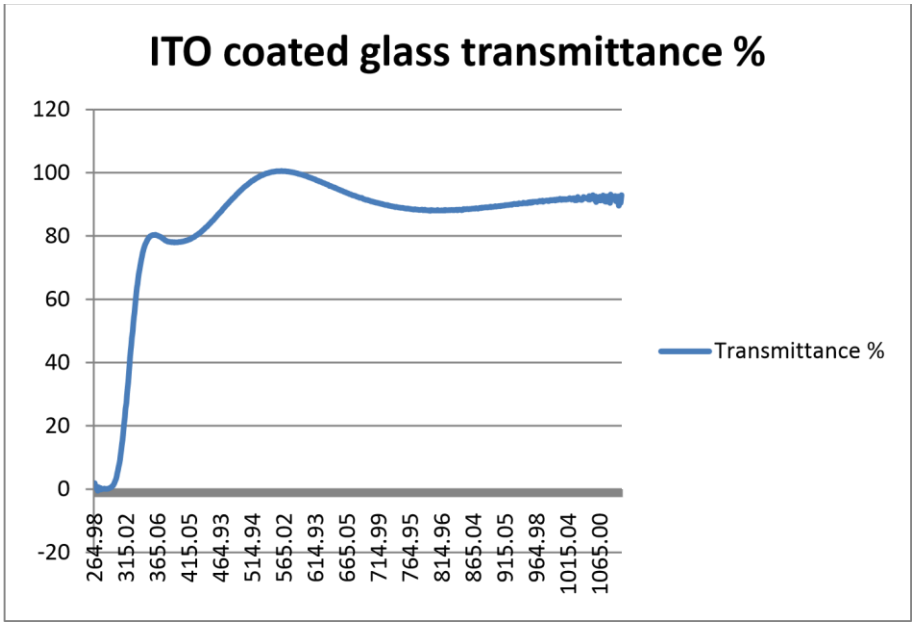


Figure 19: Transmittance (%) vs. Wavelength (nm) of ITO Film

5.0 CONCLUSION AND RECOMMENDATIONS

Conclusion

Optical transmittance and reflectance of GZO and ITO films were investigated based on literature review. They both have high transparency in the visible region and high reflectivity to IR radiation starting from 1500 nm to higher wavelength. None of these films completely reflects IR radiation with wavelengths in the range of 700 nm to 1500 nm which contributes to generation of heat most. However, reflecting the wavelengths of above 1500 nm still reduces heat generation significantly. Many factors such as doping concentration and thickness of the films affect reflectivity of the films due to their effect on shifting the plasma frequency. Increasing doping concentration and thickness of the GZO films until a certain limit improves IR reflectivity of GZO films, but it is not easy to formulate these factors precisely. In nanoparticle ITO films, reducing the particle size improves transmittance of the films in the visible light region and their reflectance in the IR region. Particle size seems to play an important role in the optical properties of ITO films.

Transmittance tests were done on a Plexiglas, glass slide, and ITO coated glass slide. Plexiglas and glass have a high transparency to visible and near IR radiation. They need to be coated with IR reflective coatings to reduce generation of heat due to IR radiation. ITO coated glass also showed high transparency to visible and near IR radiation. However, the ITO test results seemed to have some measurement errors.

Recommendations

Further investigation and experimentation is recommended to fully understand and formulate doping concentration and film thickness of GZO and ITO to achieve optimal IR reflectivity within the 700 to 1500 nm wavelength region while maintaining visible light transparency. In regards to ITO coating, reduced nanoparticle size is recommended to improve the desired visible and IR transparency and reflectivity of the film. Although IR reflectivity within the 700 to 1500 nm wavelength of GZO and ITO coating is not well understood in this study, to reduce heat generation, they are still recommended as a coating material due to their reflectivity to IR with wavelengths of above 1500 nm which also play a role in generation of heat.

REFERENCES

[1] A. Bendiganavale, V. Malshe, “Infrared Reflective Inorganic Pigments,” *Recent Patents on Chemical Engineering*, vol.1, no. 1, pp. 67-79, 2008.

[2] E. Fortunato, V. Assunção, A. Gonçalves, A. Marques, H. Águas, L. Pereira, I. Ferreira, P. Vilarinho and R. Martins, "High quality conductive gallium-doped zinc oxide films deposited at room temperature," *Thin Solid Films*, vol. 451-452, pp. 443-447, Mar. 22, 2004.

[3] J. L. Zhao, X. W. Sun, H. Ryu and Y. B. Moon, "Thermally stable transparent conducting and highly infrared reflective Ga-doped ZnO thin films by metal organic chemical vapor deposition," *Optical Materials*, vol. 33, pp. 768-772, Apr. 2011.

[4] Z. Li, Z. Chen, W. Huang, S. Chang and X. Ma, "The transparence comparison of Ga- and Al-doped ZnO thin films," *Appl. Surf. Sci.*, vol. 257, pp. 8486-8489, Aug. 1, 2011.

[5] Internet: http://en.wikipedia.org/wiki/Plasmon , [May. 30, 2011].

[6] Internet: http://engr.sjsu.edu/cme/MatELabs/MatE153/Ch7%20Optical%20Absorption.pdf, [Jun. 5, 2011].

[7] Internet: http://display.kaist.ac.kr/SSP2010/bandgapI.pdf , [Jun.4, 2011].

[8] Y. H. Kim, J. Jeong, K. S. Lee, B. Cheong, T. -. Seong and W. M. Kim, "Effect of composition and deposition temperature on the characteristics of Ga doped ZnO thin films," *Appl. Surf. Sci.*, vol. 257, pp. 109-115, Oct. 15, 2010.

[9] Internet: Google/search/ MOSS-BURSTEIN EFFECT (Expt. B1O), [Jun. 10, 2011]

[10] Y. S. Jung, H. W. Choi, Y. S. Park, K. H. Kim, W. J. Kim, “Effects of Substrate Temperature on the Properties of Ga-doped ZnO Prepared by Using a FTS System,” *Journal of the Korean Physical Society*, Vol. 57, No. 6, pp. 1909-1913, December 2010.

[11] Internet: http://en.wikipedia.org/wiki/Extinction_coefficient, [Jul. 1, 2011]

[12] E. Song, Y. H. Kim and Y. S. Kang, "Preparation of indium tin oxide nanoparticles and their application to near IR-reflective film," *Current Applied Physics*, vol. 6, pp. 791795, Jul. 2006.

[13] Internet: http://en.wikipedia.org/wiki/Sol-gel, [Jul. 2, 2011]

[14]Internet: http://en.wikipedia.org/wiki/Poly%28methyl_methacrylate%29, [Jul. 1, 2011]

[15] Internet: http://www.plexiglas.com/literature/pdf/80.pdf, [Jul. 10, 2011]

[16] Internet: http://www.plexiglas.com/acrylicresin/technicaldata/properties/optical/refractiveVLDwave, [Jun. 30, 2011]

[17] Internet: http://www.atoglas.com/literature/pdf/105.pdf, [Jul. 20, 2011]