Thermochromic and opacity behaviors in vanadium dioxide nanofilms: a theoretical study

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Abstract
Vanadium dioxide nanofilms are one of the most essential materials in electronic applications like smart windows. Therefore, studying and understanding the optical properties of such films is crucial to control these properties. To this end, this work focuses on investigating the opacity as a function of the energy directed at the nanofilms. The results show different opacity behaviors at different wavelength ranges (ultraviolet, visible, and infrared). The opacity possesses a redshift during the changes at the three phases. Regarding the infrared region, the lowest opacity value is achieved at the insulator phase and it increases to the highest value at the metal phase. In the visible region, the opacity behavior remains similar in the three phases. It is worth noting that the lowest opacity is found for thinner nanofilms. Since both the refractive index and the extinction index are among the most essential optical constants, hence, both of them were compared with the experiment results, and an excellent agreement is achieved between them.

1. Introduction

Studying Insulator–Metal Phase Transition (IMPT) in some materials like vanadium dioxides has attracted substantial research attention from both industry and academia in the last few years. This is due to their unique characteristics denoted by the optical properties that can be tuned among semiconducting, metallic, and insulating behavior [1,2]. To this end, several research studies have investigated vanadium dioxides. These studies have resulted in a thorough perception of the processes that take place during phase transition in vanadium oxides. However, such a comprehensive perception only exists for specific vanadium dioxide. The phase transformations in other oxides of the Magneli series such as [VO2, V2O3, V6O13, V3O5, V4O7, V6O11], have not been considered by researchers [3].

Vanadium dioxide is defined as a dual compound with individual physical and chemical characteristics. As such, it has gained the interest of materials researchers and scientists due to its practical and industrial applications. Interestingly, vanadium oxide exists in numerous polymorphic phases, such as VO2 (A), VO2 (B), VO2 (M), VO2 (R). Recent VO2 (C), VO2 (D), VO2 (M), and VO2 (R) are considered to be more stable thermodynamic, which have the thermochromic ability. Besides, VO2 (M) undergoes a reversible phase turn to VO2 (R) at a critical temperature of 68 °C [4]. In addition, the phase transition produces a change in the material’s properties, like optical, electrical, magnetic, and other functional characteristics [5]. For example, the semiconductor VO2 (M) is transparent for IR radiance while the metallic VO2 (R) is IR reflectant. As such, VO2 (M) can be considered as a reasonable potential choice in applications such as thermal sensors; optical switching
devices; smart window materials; thermochromic; and electrochromic devices. To this end, the metastable phase VO$_2$ (B) is being examined for its possible application as cathode material because of its layered structure [6]. Materials that are impermeable to light are named opaque, which means that the spectrum is completely absorbed by the material or a complete reflection of it. The crystal structure of the material is often responsible for the optical penetration, where the chemical composition, especially in the presence of structural defects of these materials, has what are called absorption centers. This implies that it has the property of selecting the frequencies of the spectrum, as it can absorb part and reflect the rest of the parts.

Typically, semiconductors are transparent in the (NIR) region and absorber in the (VIS) region, while dielectrics exhibit strong absorption in the (UV) region. In semiconductor materials, the fundamental absorption edge is in the energy range of (0.5–2.5) eV; that corresponds to $\lambda \sim (500–2500) nm$. Within a small energy range around the fundamental absorption edge, semiconductors are ideally transferred from high transparency to total opacity. However, the presence of free conduction electrons or holes, impurities, and other defects may impact the transparency of the semiconductors and dielectric materials at photon energies smaller than the bandgap [7].

The total frequency-dependent opacity can be determined as the sum of the contributions of different physical processes. Opacity is not an intrinsic property of material rather it mainly depends on the thickness just like the emissivity. For instance, lower emissivity is the property of a thinner material. Typically, the emissivity can be calculated (experimentally) at a direction normal to the surface [8]. Regarding the electronic devices, the photon energy range is covered the fundamental absorption edge that the substance transfers from complete transparency to total opacity. As optic transmittance affords quickly and accurately information in the spectral range. Several attempts have been carried out to improve the techniques that allow the retrieval of opacity to several degrees of transparency. As optic transmittance affords quickly and accurately information in the spectral range. Several attempts have been carried out to improve the techniques that allow the retrieval of the thickness and the optical constants of the thin films from measuring the transmittance only [9].

This study focuses on studying the effect of changing the wavelengths of the directed energy of ultraviolet, visible, and infrared spectra on the vanadium dioxide nanofilm and calculating the opacity ratio as a function of temperature. Besides, the transitional phases of vanadium dioxide of the insulator, semiconductor, and metal, along with the opacity are investigated in this paper as a function of the film thickness with range (1–100) nm.

### 2. The model

VO$_2$ gained a particular interest since it is transitioned from the optically insulating monoclinic phase to the metallic rutile phase, which is optically opaque tetragonal near temperature (68 °C). The transition (IMT) in VO$_2$ nanofilm can be achieved by applying thermal [10], optical [11], or electrical stimuli [12]. The behavior of atoms in any material when applying an electric field is only an expression of the permittivity or the so-called dielectric constant [13]. Lorentz interactively modeled this behavior between the electric field and the electron charge that is mass bound to the atom’s nucleus by a spring. Therefore, this behavior causes the spring to stretch and compress, which results in the electron turning into an oscillating motion. The oscillations are concerning with the electronic arrangement, the atomic orbital level, and the density of states, which are given as: [14, 15]

$$\varepsilon_{\text{eff}}(\omega) = \varepsilon_{\infty} + \sum_n \frac{A_n}{(E_n^2 - \omega^2) - i\Gamma_n B_n},$$  \hspace{1cm} (1)

where $\varepsilon_{\infty}$ refers to the maximum permittivity for frequency, parameter $n$ is the sum of oscillators around $\varepsilon_{\infty}$ ($n = 2$), $A_n$, $E_n$, and $B_n$ the amplitude, energy, and damping of the oscillators respectively, which represent the parameters used in an oscillator model to estimate the permittivity of VO$_2$ nanofilm in its two-phases metallic and insulating. Table 1 provides the parameters of equation (1) as given in [16].

The transition phase produces a change in the characteristics of the material which means, the characteristics of each phase seem to be separated from each other. As such, the substance is a tunable optic material [17]. The effective-medium theories (EMTs) for example; the Bruggeman formalism and the Looyenga mixing rule [15, 16, 18] were applied to estimate the permittivity of VO$_2$ nano-films approximately, within the IMT when insulating and metallic domains coexist. In this paper, the Looyenga rule is used as a function of both wavelength and temperature, which is given as

$$\varepsilon_{\text{VO2}}(T) = f(T) \times \varepsilon_{\text{ins}} + [1 - f(T)] \times \varepsilon_{\text{metal}}.$$ \hspace{1cm} (2)

The equation above represents the relation between the permittivity of VO$_2$ with temperature, $\varepsilon_{\text{VO2}}(T)$, which resulted from the permittivity in the metal phase, $\varepsilon_{\text{metal}}$ and the insulator phase $\varepsilon_{\text{ins}}$, the Boltzmann’s function for this study is given in [19, 20]. This is in contrast to some studies that adopted the Fermi–Dirac function [16]. At the same time, it can be defined as a filling fraction. In other words, it is defined as the volume fraction that depends on the temperature, $f(T)$, which is changed from (0 to 1) and depends on the grading of nanofilm during the transition to the metal phase [15]. $f(T)$ can be expressed as [19, 20].
expression behavior of the atoms when applied the electric field with electrons charge that is supposed as a bound mass to the atom’s nucleus, such as spring. This interaction leads to expansion and compression of the spring and sets the electron at oscillating motion. The oscillations are regarding the electronic arrangement and the density of states at the levels of atomic orbitals [14, 24].

The complex permittivity and the complex refractive index are given in [13, 25] as

\[ \varepsilon = (n^2 + k^2) + i(2nk), \]  

where \( n \) is the refractive index and \( k \) is the extinction coefficient. Parameter \( k \) plays an essential role in determining the optical absorption of solids, and \( k \) is associated with the incident electric field at the damping oscillation amplitude. Also, \( k \) is related to decay. Therefore, \( k \) (besides \( n \)) is mainly controlled by the electric field of the electromagnetic wave and its interaction with the solids. In addition, \( \alpha \) is the absorption coefficient denoted by [17] as

\[ \alpha = \frac{4\pi k}{\lambda}. \]  

When the light proceeds from air into \( VO_2 \) nanofilm, different interactions of matter with light have occurred. Part of the light is transmitted through the matter, while other parts are either absorbed by the material or reflected at the interface between the two media. The \( I_0 \), intensity of the beam falling on the surface of the solid medium must be equal to the sum of the intensities of transmitted \( (I_T) \), absorbed \( (I_A) \), and reflected \( (I_R) \) beams, or \( I_0 = I_T + I_A + I_R \). The transmission is \( T = I_T/I_0 \), the absorption is given \( A = I_A/I_0 \), the reflection is given as \( R = I_R/I_0 \), and the transparent \( = T \sim 1 \). Therefore, Opacity \( = T \sim 0 \), for this reason, the opacity is obtained as \( A + R = 1 - T \). Since the reflectivity is low, it is neglected. Then, the opacity is calculated from the relation as [26].

\[ \text{Opacity} = Abs, \quad 100\%. \]  

where \( Abs \) is the absorbance at \( \lambda \) (nm).

It is important to mention that the transmittance can be converted to the absorbance using the Lambert-Beer equation [26], therefore, the absorbance can be given as.

| Phase   | \( \varepsilon_{\text{osc.}} \) | Parameters | osc.1 | osc.2 |
|---------|---------------------------------|------------|-------|-------|
| Insulator | 3.4 | En | 3.8 | 1.2 |
|          |     | An | 33  | 2.1  |
|          |     | Bn | 1.4 | 1.3  |
| Metal   | 4.5 | En | 3.2 | 0.6  |
|          |     | An | 13  | 5.3  |
|          |     | Bn | 1.1 | 1    |

\[ f(T) = f_{\text{max}} \left( 1 - \frac{1}{\exp \left( \frac{T - T_i}{W} \right) + 1} \right), \]  

where \( f_{\text{max}} \) is assumed to be about 0.95, which is defined as the volume fraction of the metallic phase at the highest temperature [19]. We hypothesize that the transition in \( VO_2 \) nanofilm from the insulator phase to the metallic phase by heating procedure, in which the transition temperature is given by [20].

\[ T_i = \frac{T_{\text{max}} + T_{\text{min}}}{2}. \]  

The expression above is obtained by identifying the critical transition temperature through heating \( (T_{\text{t,max}}) \), 68 °C, and cooling temperature \( (T_{\text{t,min}}) \), 62 °C. As such, we can calculate \( W \), the width of the transition, and include information about the temperature of the IMT transitions for \( VO_2 \) nanofilm, which is calculated by [16, 21] and given as.

\[ W = T_{\text{t,max}} - T_{\text{t,min}}. \]  

The expression above remains fixed at \( W = 6 \) °C [22], the permittivity or dielectric constants are a good expression behavior of the atoms when applied the electric field on the material [23]. Lorentz explained this behavior by the interaction of the electric field with electrons charge that is supposed as a bound mass to the atom’s nucleus, such as spring. This interaction leads to expansion and compression of the spring and sets the electron at oscillating motion. The oscillations are regarding the electronic arrangement and the density of states at the levels of atomic orbitals [14, 24].

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|          |     | Bn | 1.1 | 1    |
The transitions may occur between two atoms that have electrons not involved in the formation of σ bond or π bond [27]. The different molecular pathways are arranged according to the energy levels and the highest required energy for the electronic transition is σ—σ* followed by the transition n—σ* then the transition π—π*, which considers the minimum necessary for the occurrence of electronic transition [22]. In the ultraviolet region, the first and second types of transitions have occurred while the last type of transitions occurs in the visible region. It is worth noting that both π—π* and n—π* transitions do not change the chemical composition of the material. While, it changes other types of transitions resulting in the most destructive in the range of (100–290) nm, and it records the highest values of the absorption coefficient. In the infrared region, the vibrational and rotational transitions of molecules have occurred, and there is not no electronic irritation occurs.

In this paper, the temperature width of $W = 6$ °C (which is defined as the difference between cooling and heating) was chosen similar to our previous study [23]. The ISM transitions of VO$_2$ nanofilm in the temperature ranges of (20–50) °C, (60–70) °C, and (80–100) °C are assigned to the insulator, semiconductor, and metal phases respectively. When the width is large, the phases are clearer than that of the small width due to the temperature difference, and the curves were divided according to the phase. Figure 1 presents the refractive index of (a) the ultraviolet region, (b) the visible region, and (c) the infrared region for the insulator phase (20–50) °C, the semiconductor phase (60–70) °C, and metal phase (80–100) °C.

![Figure 1](image_url)

**Figure 1.** The Refractive index of VO$_2$ nanofilm for (a) the ultraviolet region, (b) the visible region, and (c) the infrared region for the insulator phase (20–50) °C, the semiconductor phase (60–70) °C, and metal phase (80–100) °C.

The criterion between gain $\eta$ and loss $\sigma$ is defined as the difference between cooling and heating, and the criterion between gain $\eta$ and loss $\sigma$ is defined as the difference between cooling and heating. From figure 1(a), it is noticed that all the phases have coincided with the behavior of the refractive index, which means that the electronic transitions of all phases occur with the same energies and mechanism. This makes the polarized charges of all phases equally rotate with an electric field. In the infrared region, figure 1(c), it is seen that

$$Abs = \frac{X - \sigma}{2.303}$$

where $X$ is the thickness of the VO$_2$ nanofilm.

### 3. Results and discussions

The electromagnetic spectrum covered in this study includes three regions which are ultraviolet, visible, and infrared. When interacting with matter, this spectrum is characterized by different transitions from one region to another. The transitions may occur between two atoms that have σ bond or π bond, or in an atom has electrons not involved in the formation of σ bond or π bond [27]. The different molecular pathways are arranged according to the energy levels and the highest required energy for the electronic transition is σ—σ* followed by the transition n—σ* then the transition π—π*, which considers the minimum necessary for the occurrence of electronic transition [22]. In the ultraviolet region, the first and second types of transitions have occurred while the last type of transitions occurs in the visible region. It is worth noting that both π—π* and n—π* transitions do not change the chemical composition of the material. While, it changes other types of transitions resulting in the most destructive in the range of (100–290) nm, and it records the highest values of the absorption coefficient. In the infrared region, the vibrational and rotational transitions of molecules have occurred, and there is not no electronic irritation occurs.

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It is known that the dielectric constant is the measure of the ability of the material to focus the lines of the internal electric field. It consists of two parts, the first, is the refractive index, which represents the amount of gain, the second is the extinction coefficient, which represents the amount of loss. The criterion between gain and loss here is the uniformity of the charge aggregates revolving around the electric field, in other words, the polarizability of the charge carriers.

It can be seen from figure 1(a) that the process of maintaining the rotation of polarized charges towards the electric field does not take place in this region as for all phases of vanadium dioxide. It is found in our calculations that; the insulator does not rotate towards the electric field as a result of the occurrence of electron transitions of large energy, and the particles move with a great force. Here, it can be said that the net polarization becomes low due to the difficulty of aligning the direction of the electric field. Gradually, the charges of the semiconductor phase rotate with the direction of the field due to the low energy of the electronic transitions compared to the dielectric phase. Hence, the phase of the metal has the highest refractive index in this region. In the visible region, the uniformity of the rotation of polarized charges increases with an electric field. From figure 1(b), it is noticed that all the phases have coincided with the behavior of the refractive index, which means that the electronic transitions of all phases occur with the same energies and mechanism. This makes the polarized charges of all phases equally rotate with an electric field. In the infrared region, figure 1(c), it is seen that...
the refractive index of the insulator phase is higher than other phases because the electronic transitions overcome the vibrational and rotational transitions. Also, the transitions in the semiconductor phase are less than those of the metal phase, and therefore the refractive index of the semiconductor phase is higher than that of the metal phase.

The extinction coefficient is considered the evidence of losses resulting mainly from the dipoles motion by the effect of an electric field, or maybe caused by ions and phenomena of relaxation and dipole polarization [28]. Figure 2 shows the extinction coefficient of VO$_2$ nanofilm (a) the ultraviolet region, (b) the visible region, and (c) the infrared region.

In figure 2(a), the losses are graded from the insulator-metal phase through the semiconductor phase. But, the highest losses are between 100 nm to 290 nm, which are known to be the most destructive radiation. In the visible region, it was noticed a little difference between the three phases. This means there are equal quantities of losses at the same time with the same mechanism. On the other hand, the losses are less than those in the UV region. In the IR region, the extinction coefficient depends on the absorptivity of radiation as well as its transition levels.

The losses of the insulator phase are the lowest followed by the semiconductor phase and then the metal phase. It may be said that the transition states of the carriers are almost constant due to the proven properties of these phases (according to Mott transformations). This shows that the main effects of the strong U electron-Coulomb repulsion or Hubbard interaction are conserved [18].

Figures 3(a) and (b) indicate the behavior of both the refractive index and the extinction coefficient between our calculations and the published experimental results for both the metallic phase and insulator phase [29]. It is noticed that the published experimental results in the insulator phase, are very close to the theoretical results of the extinction coefficient, while in the metallic phase, our model has the lowest loss of the extinction coefficient at short wavelengths, where electronic transitions prevail in this region, but do not coincide at long wavelengths, because theoretical assumptions often tend to be ideal. The heat at the metallic phase may lead to a greater number of transitions, especially since the dominant type of transition is vibration and rotation, which can occur with very little energy, in addition, the method of preparing the material and the practical conditions that go through the experiment. Figure 4 represents the absorption coefficient for each of the three phases of the VO$_2$ nanofilm, for (a) the ultraviolet region, (b) the visible light region, and (c) the infrared region, they show that; the values of the absorption coefficient differ according to the phase, besides its values also vary according to the incident wavelength.

In the ultraviolet and visible regions, a significant increase in the absorption coefficient is observed due to the electronic transitions in the VO$_2$ molecule. While in the infrared region, the vibrational transitions and/or rotational transitions occur, which do not require high energy as mentioned previously, and this region exhibits a relatively low absorption coefficient. On the other hand, the absorption coefficient is changed due to changing the phase. In the insulator phase, the highest values of the absorption coefficient are observed in the ultraviolet region, where the transitions (mentioned at the beginning of the discussion paragraph) activate the first type or and the second type due to the large size of the energy gap in the insulator. A small energy gap of the semiconductor phase, less energy for the transition is needed and it is even lower in the metal phase. In the infrared region, the vibrational and rotational transitions are activated in the metal, and they decrease at the semiconductor phase and they more decrease at the insulator phase.
Both transparency and opacity are contrasted with each other in terms of the scientific content of both the mechanism and behavior. But, what are the boundary conditions that make vanadium dioxide behave as transparent, and sometimes as opaque?

Figure 3 represents the results of the opacity in the violet region in the left column, followed by the visible region in the middle column, and finally the infrared region in the right column. On the other hand, the rows represent the phases. The top row represents the insulating phase, the middle two rows represent the semiconductor phase, and the bottom row represents the metal phase.

In the ultraviolet region, a redshift is noticed from figure 5, the curve is divided into two parts, the first part is at wavelengths less than 290 nm where the opacity in all phases is very low due to the penetration of the ultraviolet spectrum in the material, the type of electronic transitions which require high energies and the chemical composition of the material. Therefore, most of the danger that the ultraviolet rays may result in should be considered. The second part is at wavelengths greater than 290 nm, especially closer to the visible region, the opacity decreases due to the number of photo-polarized carriers that maintain their continuous rotation with the direction of the electric field and the mechanism and the electronic transitions type. Thus, the refractive index values will converge causing the material to allow light to pass through space. It can also be seen that the insulator phase shows more opacity, while the metal phase is the least opaque. This is explained according to the electronic transitions and their compatibility with the optical energy gap of the three phases, where the insulator phase exhibits a wide energy gap resulting in fewer transitions. While the number of electronic transitions in the semiconductor phase is high due to decreasing the energy gap especially for the third
type of transitions because the required energy is less than what the insulator phase needs. As well as, the electronic transitions increase in the metal phase owing to vanishing its energy gap. In the visible region, the behavior of the three phases is similar due to the similarity of the electronic transition mechanisms and types. However, the number of transitions is varied. The highest number of transitions was found in the metal phase followed by the semiconductor phase and then the insulator phase. Additionally, the highest opacity is observed at the insulator phase and it decreases at the semiconductor and metal phases. It is also noticed that the opacity in this region is greater at wavelengths close to the ultraviolet region with flat curves of at the rest wavelengths.

In the infrared region (the right column in figure 5), the opacity behavior is opposite to in the results of the ultraviolet and visible regions due to different types of transitions in this region, where the vibrational and rotational transitions are predominant. In addition, there is a correlation between the thicknesses of the nanofilm the opacity in all phases, since the thicker the nanofilm the higher the opacity will be.
4. Conclusions

Materials that are impermeable to light are named opaque, which means that the spectrum is either completely absorbed or completely reflected by the material. The crystal structure of the material is often responsible for the optical penetration, and the chemical composition, especially in the presence of the structural, defects in these materials usually called the absorption centers. This means it has the property of selecting the frequencies of the spectrum, and it can absorb some parts of the electromagnetic radiation and reflect and/or transmit other parts. This is what was seen in our results, where the regions that suffered from opacity are found to have high absorption.

It was previously explained that electronic transitions are predominant in the ultraviolet and visible regions. If the electron orbits are quantized, they can absorb a certain amount of light or a specific photon and do not violate the rules of selection. If the material does not have electrons available above it in the range associated with visible light, then it violates the rules of selection, which means that there is no appreciable absorption at the atomic or molecular level which makes them ideal transparent materials. Therefore, vanadium dioxide visible light, then it violates the rules of selection, which means that there is no appreciable absorption at the atomic or molecular level which makes them ideal transparent materials. Therefore, vanadium dioxide influenced by the ultraviolet spectrum exhibits high opacity at the insulator and semiconductor phases, while the opacity decreases at the metal phase due to the difference in the structure and the transmission mechanisms. While, the transitions in the infrared region are vibrational and rotational, and the absorption depends on the chemical bonds, the frequencies of atomic or molecular vibrations, and the rules of selection. In this type of transition, the spectrum wave frequency must be equal to the vibrational frequencies of the particles of the material so that the energy of the spectrum wave is absorbed by the material and then the vibrational motion is converted into heat energy. Each atom or molecule has its natural vibrational frequencies, so it will selectively absorb different frequencies in the infrared spectrum. This is why the opacity of the metal phase is higher than that of the insulating and semiconductor phases because the metal contains a lot of free electrons, so the absorption and then the transition is higher than those of other phases.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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References

[1] Gurvitch M, Luryi S, Polyakov A and Shabalov A 2007 VO2 films with strong semiconductor to metal phase transition prepared by the precursor oxidation process Solution–processed phase-change VO2 metamaterials from colloidal Vanadium Oxide (VOx) nanocrystals J. of Applied Physics 102 033504
[2] Taejong P, Sung-Hoon H and Gaulding E 2014 Solution–processed phase-change VO2 metamaterials from colloidal Vanadium Oxide (VOx) nanocrystals ACS Nano. 8 787–806
[3] Barra H M, Chen S K, Tamchek N, Talib Z A, Lee O J and Tan K B 2021 Nanostructured VO2 (A) and VO2 (M) derived from VO2 (B): facile preparations and analyses of structural, thermal, optical and thermophysical properties Materials Science (Medžiagotyra). 27 3
[4] Ilinskii A V, Nikulin E I and Shadrin E B 2020 Comparative analysis of semiconductor-metal phase transition mechanisms in vanadium oxides (VOx and VO2) Physics of Complex Systems 1 3
[5] Yu J-H, Nam S-H, Lee J W and Boo J-H 2016 Enhanced Visible Transmittance of Thermochromic VO2 Thin Films by SiO2 Passivation Layer and Their Optical Characterization Materials 9 556
[6] Chambouleyron J M 2021 Handbook of Nanomaterials and Nanocomposites for Energy and Environmental Applications (Berlin: Springer) (https://doi.org/10.1007/978-3-630-36268-3)
[7] Da Silva Oliveira C I, Martinez-Martinez D, Al-Rjoub A, Rebouta L, Menezes R and Cunha L 2018 Development of a statistical method to help evaluating the transparency/opacity of decorative thin films Applied Surface Science 438 51–8
[8] Lamsal C 2015 Electronic, thermoelectric and optical properties of vanadium oxides: VO2, V2O3 and V2O5 PhD Thesis New Jersey Institute of Technology (https://digitalcommons.njit.edu/dissertations/100)
[9] Gurvitch M, Luryi S, Polyakov A and Shabalov A 2007 Nonhysteretic behavior inside the hysteresis loop of VO2 and its possible application in infrared imaging Applied Physics 102 033504
[10] Brassard D, Fourmaux S, Jean-Jacques M, Keiffer J C and El Khakani M A 2005 Grain size effect on the semiconductor-metal phase transition characteristics of magnetron-sputtered VO2 thin films Appl. Phys. Lett. 87 035190
[11] Kuebler C, Ehrike H, Huber R, Lopez R, Halabica A, Haglund R F and Leitenstorfer A 2007 Coherent structural dynamics and electronic correlations during an ultrafast insulator–to–metal phase transition in VO2 Phys. Rev. Lett. 99 116401
[12] Gentle A and Smith G B 2008 Dual metal–insulator and insulator–insulator switching in nanoscale and Al doped VO2 J. Phys. D: Appl. Phys. 41 015402
[13] Wegener M 2005 Extreme Nonlinear Optics, An Introduction 1st edn (Berlin: Springer) (https://doi.org/10.1007/b137953)
[14] Currie M, Mastro M A and Wheeler V D 2017 Characterizing the tunable refractive index of vanadium dioxide Opt. Mater. Express. 7 1697–707
[15] Iken O, Bouyghf H, Bouazaoui K, Agounoun R and Rahmoune M 2017 Numerical characterization of vanadium dioxide thin films applied to thermal building insulation: determination of dielectric constant using PSO algorithm Int. J. Eng. Technol. 9 3836–40
[16] Currie M, Mastro M A and Wheeler V D 2018 Atomic layer deposition of vanadium oxioide and a temperature-dependent optical model Journal Vis Exp. 135 e57103
[17] Mrigal A, Gana L, Addou M, Bahedi K, Tensamasri R, Cherrad H, Jouda Z, El and Zinou J 2020 Temperature effect on structural and optical properties of V_2O_5 thin films prepared by spray pyrolysis technique MATEC Web of Conferences 307 01033
[18] Gentle A R, Smith G B and Maaroof A I 2009 Frequency and percolation dependence of the observed phase transition in nanostructured and doped VO_2 thin films Journal of Nanophotonics 3 031505
[19] Jepsen P U, Fischer B M, Thomann A, Helm H, Suh J Y, Lopez R and Haglund J 2006 Metal-insulator phase transition in a VO_2 thin film observed with terahertz spectroscopy Phys. Rev. B. 74 205103
[20] Ling F, Zhong R, Huang and Zhang B 2018 A broadband tunable terahertz negative refractive index metamaterial Sci. Rep. 8 9843
[21] Xygkis M, Gagoudakia E, Zouridi L, Markaki O, Aperathitis E, Chrissopoulou K, Kirakidis G and Binas V 2019 Thermochromic behavior of VO_2/polymer nanocomposites for energy saving coatings Coatings. 9 163
[22] Jager M F, Ott C, Kraus P M, Kaplan C J, Pouse W, Marvel R E, Haglund R R, Neumark D M and Leone S R 2017 Tracking the insulator-to-metal phase transition in VO_2 with few-femtosecond extreme UV transient absorption spectroscopy PNAS 114 9558–63
[23] Abdul-Ameer N M, Khaleel I H, Abdul Hasan S Q and Abdulrid M C 2021 The Effect of temperature width on dielectric constant of VO_2 Key Engineering Materials 886 108–16
[24] Iken O, Agounoun R, Rahmoune M, Sbai K, Zoubir A and Saadani R 2017 Numerical study of thermo-chromic properties of VO_2-polymer composites coatings applied to building thermal insulation Int J Eng Technol. 9 916–22
[25] Lamsal C and Ravindra N M 2013 Optical properties of vanadium oxides-an analysis J. Mater. Sci. 48 6341–51
[26] Oleyaei S A, Zahedi Y, Ghanbarzadeh B and Moayed A A 2016 Modification of physicochemical an thermal properties of starch films by incorporation of TiO_2 nanoparticles International Journal of Biological Macromolecules 89 256–64
[27] Merenda P and Sol N 1977 Vapor phase epitaxy of pure VO_2 and V_1–xCrxO_2 Journal of Crystal Growth 80 195–9
[28] Wan C, Zhang Z, Woolf D, Hessel C M, Rensberg J, Hensley J M, Xiao Y, Shahsafi A, Saliman J and Richter S 2019 On the optical properties of thin-film vanadium dioxide from the visible to the far infrared Ann. Phys. 531 1900188
[29] Joushaghani A 2014 PhD thesis Graduate department of electrical and computer engineering, University of Toronto (http://hdl.handle.net/1807/68313)