Study of the Absorptance of a Thin Layer of the Vanadium Dioxide

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Abstract

Objectives: This work shows the study of the evolution of the CoeffA absorptance of a thin layer of VO₂ according to the energy of the incidental photon in order to deduce its optical response in the average I.R, the close I.R, the remote I.R, the visible spectrum and the U.V. Methods/Statistical Analysis: We have used the model of Drude for the thin layer of VO₂ in the metal state, and the model of Lorentz for the semiconductor state of this thin layer in order to simulate the optical functions of this material, and in particular the absorptance. An analysis of the maxima and minima of this optical function was made in the two states, semiconductor and metal, according to the model used. Findings: In the semiconductor state of the vanadium dioxide, we noticed that the number of oscillators of Lorentz influences clearly the description of the absorptance and these specific points: maxima and minima. Indeed, the model with seven oscillators is strongly maintained if compared to that of four oscillators. Whereas in the metal state of this thin layer of the vanadium dioxide, the model of Drude with only one oscillator describes the variation of CoeffA according to the energy ω (ev) of the incidental photons in the spectrum from the infra-red to the ultraviolet ray. Application/Improvements: This general study allows the incorporation of this intelligent material in various technological nano applications, like the solar air-conditioners and the thermal pumps.

Keywords: Metal State, Semiconductor State, Thin Layer, The Absorptance, The Infra-Red, Vanadium Dioxide

1. Introduction

The vanadium dioxide VO₂ has currently become relevant to nanotechnology researchers. It is a thermochromic material which can make a transition of a reversible phase between the semiconductor state and the metal state at a critical temperature 68°C. The semiconductor state of the vanadium dioxide is characterized by a gap of 0.7 ev⁵,⁶. Among its industrial applications, we cite the infra-red detectors, the ultra-violet⁷,⁸, the optical memories whose principle is founded on the evolution of its hysteresis cycle⁹ and the intelligent panes⁹,¹⁰. Various theoretical and practical studies have been carried out to explain the dielectric function's response of its two phases, semiconductor and metal. The dielectric function of the massive vanadium dioxide was developed by using the reflectivity and the transmissivity method¹¹. The dielectric response of the vanadium dioxide is extracted¹². The ellipsometric spectroscopy for the determination of the constant optics of VO₂ thin layers has recently been used¹³. We are interested in this paper in the study and simulation by Maple of the coeffA (the absorptance) of a thin layer of VO₂ in the semiconductor state at a temperature θ < 68°C, on the one hand, and in the metal state at a temperature θ > 68°C, on the other hand. The absorptance is defined as follows:

\[ \text{coeffA} = \frac{I_a}{I_0} = 1 - (R + T) \]  

(1)

\( I_0 \) : The incidental intensity, \( I_a \) : The absorptive intensity by the vanadium dioxide

And we are interested as well in the comparison of the ratio T/R in the two states, semiconductor and metal. For the semiconductor VO₂, we retain the model of Lorentz of seven oscillators¹⁴–¹⁶.
This work enables us to see some information on the bands’ structure of VO₂ semiconductor during the electronic transitions between the valence band and the conduction band, as well as the electronic polarizability during an excitation by an electromagnetic wave in various spectral fields: The I.R, the visible spectrum and the U.V.

2. Methods

2.1 Drude’s Model

For the vanadium metal dioxide, we use Drude’s model for the dielectric function:

\[ \varepsilon(\omega) = \varepsilon_\infty + \frac{\omega_p^2}{\omega^2 + i\Gamma_d \cdot \omega} \]  

(2)

Where:
- \( \varepsilon_\infty \): The dielectric constant's electronic transition high frequency.
- \( \Gamma_d \): The frequency of collision.
- \( \omega_p \): The plasma frequency.
- \( \omega \): The frequency of the incidental photon in electron volt.
- \( \varepsilon \): The complex dielectric constant of the material.

The Equation (2) becomes:

\[ \varepsilon(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega \cdot (\omega - i\Gamma_d)} \]  

(3)

We, thus, write:

\[ \varepsilon(\omega) = \varepsilon_1(\omega) - i\varepsilon_2(\omega) \]  

(4)

\[ \varepsilon_\infty \rightarrow 1 \]  

(5)

\[ \varepsilon_1(\omega) = 1 - \frac{\omega_p^2}{\omega^2 + \Gamma_d^2} \]  

(6)

\[ \varepsilon_2(\omega) = \frac{\omega_p^2 \cdot \Gamma_d}{\omega \cdot (\omega^2 + \Gamma_d^2)} \]  

(7)

By using this model, we can simulate the variation of the constant optics of VO₂ according to the energy \( \omega \) (ev) of the incidental photon while being based on the parameters of VO₂ film according to the Table 1 and by using an oscillator of Drude for \( \theta = 85^\circ C \)

\( f_j \): The force of the \( f \) time oscillator of Lorentz.
\( \omega_{0j} \): frequencies of resonance for the energy oscillator corresponding to the peak of absorption.
\( Y_j \): The widening of each oscillator j, knowing the damping.

We obtain:

\[ \varepsilon_1(\omega) = 1 - \frac{19,9809}{\omega^2 + 0.82^2} \]  

(7)

\[ \varepsilon_2(\omega) = \frac{16,384338}{\omega \cdot (\omega^2 + 0.82^2)} \]  

(8)

We note for this VO₂ thin layer:
- \( n \): The index of refraction of the material
- \( k \): The coefficient of extinction of the material.
- \( R \): Reflectivity of a thin layer of VO₂ for the normal incidence.
- \( T \): Transmittivity of a thin layer of VO₂ for the normal incidence.
- \( \alpha \): The absorption coefficient of a thin layer of VO₂.
- CoeffA: The absorptance.

\[ n = \frac{1}{\sqrt{2}} \left( \varepsilon_1 + (\varepsilon_1^2 + \varepsilon_2^2)^{\frac{1}{2}} \right) \]  

(9)

\[ k = \frac{1}{\sqrt{2}} \left( -\varepsilon_1 + (\varepsilon_1^2 + \varepsilon_2^2)^{\frac{1}{2}} \right) \]  

(10)

\[ R = \frac{(n - 1)^2 + k^2}{(n + 1)^2 + k^2} \]  

(11)

\[ T = \frac{(1 - R)^2 \cdot e^{-\alpha z}}{1 - R^2 \cdot e^{-2\alpha z}} \]  

(12)

Where \( Z = 82 \cdot 10^{-7} \text{cm} \) , the thickness of the VO₂ thin layer

\[ \alpha = \frac{4\pi \cdot k \cdot \omega \cdot 10^5}{12.424125} \]  

(13)

\[ \text{CoeffA} = 1 - R - T \]  

(14)

\[ \text{CoeffA} = 1 - \frac{(1 - R)^2 \cdot e^{-\alpha z}}{1 - R^2 \cdot e^{-2\alpha z}} - \frac{(n - 1)^2 + k^2}{(n + 1)^2 + k^2} \]  

(15)

Table 1. Drude parameter values of VO₂ thin films determined from the simulation of ellipsometric spectra

| Parameter | Value |
|-----------|-------|
| \( f_j \) | 0,87  |
| \( \omega_{0j} \) | 2,87  |
| \( Y_j \) | 0,77  |
| \( \omega_p \) | 4,47  |
| \( \Gamma_d \) | 0,82  |
2.2 Lorentz’s Model
In the semiconductor state of the vanadium dioxide, we use the model of Lorentz\(^{14–16}\). The dielectric function of this material is described in the following way:

\[
\varepsilon(\omega) = \varepsilon_{\infty} + \frac{(\varepsilon_1 - \varepsilon_{\infty}) \cdot \omega_0^2}{\omega_0^2 - \omega^2 + i\gamma \cdot \omega} \sum_{j=1}^{N=7} \frac{f_j \cdot \omega_{0j}^2}{\omega_{0j}^2 - \omega^2 + i\gamma_j \cdot \omega} \tag{16}
\]

We are interested in the contribution of 7 oscillators, \(N = 7\) in the following summation:

\[
\varepsilon(\omega) = \varepsilon_1(\omega) - i\varepsilon_2(\omega) = \sum_{j=1}^{N=7} \frac{f_j \cdot \omega_{0j}^2}{\omega_{0j}^2 - \omega^2 + i\gamma_j \cdot \omega} \tag{17}
\]

By means of this model and by using the Table 2, we can simulate the VO\(_2\) semiconductor's constant optics and make a comparison with those of the metal state.

Table 2. Lorenz parameter values of VO\(_2\) thin films determined from the simulation of ellipsometric spectra\(^{19}\)

| \(f_j\) | \(\omega_{0j}\) | \(\gamma_j\) | \(\omega_p\) |
|---|---|---|---|
| 0.67 | 1.02 | 0.54 | 0.04 |
| -0.46 | 1.92 | 3.02 | 0.96 |
| 1.11 | 1.39 | 0.88 | 2.38 |
| 2.38 | 3.45 | 1.34 | 1.6 |
| 1.6 | 4.28 | 2.42 | 2.02 |
| 3.4 | 7.57 | 2.24 | 0.65 |
| 0.54 | 2.98 | 0.65 | |

The permittivity complex of this material in the semiconductor state becomes:

\[
\varepsilon(\omega) = \sum_{j=1}^{N=7} \frac{f_j \cdot \omega_{0j}^2 ((\omega_{0j}^2 - \omega^2) - i\gamma_j \cdot \omega)}{(\omega_{0j}^2 - \omega^2)^2 + \gamma_j^2 \cdot \omega^2} \tag{18}
\]

\[
\varepsilon(\omega) = \sum_{j=1}^{N=7} \frac{f_j \cdot \omega_{0j}^2 ((\omega_{0j}^2 - \omega^2)^2 + \gamma_j^2 \cdot \omega^2)}{(\omega_{0j}^2 - \omega^2)^2 + \gamma_j^2 \cdot \omega^2} \tag{19}
\]

\[
\varepsilon_1(\omega) = \sum_{j=1}^{N=7} \frac{f_j \cdot \omega_{0j}^2 (\omega_{0j}^2 - \omega^2)}{(\omega_{0j}^2 - \omega^2)^2 + \gamma_j^2 \cdot \omega^2} \tag{20}
\]

\[
\varepsilon_2(\omega) = \sum_{j=1}^{N=7} \frac{\gamma_j \cdot \omega}{(\omega_{0j}^2 - \omega^2)^2 + \gamma_j^2 \cdot \omega^2} \tag{21}
\]

where :

\(\varepsilon_1(\omega)\) is the real part of the permittivity complexes as it is clearly shown in Figure 1(a) and \(\varepsilon_2(\omega)\) is its imaginary part as it is indicated in Figure1(b).

![Figure 1](image)

Figure 1. (a) The variation of the permittivities \(\varepsilon_1(\text{SC})\) and \(\varepsilon_1(\text{M})\) the vanadium dioxide according to the energy \(\omega\) (ev) of the incidental photons \(\varepsilon_1\) is the real part of the VO\(_2\) dielectric function complexes. (b) The variation of the permittivities \(\varepsilon_2(\text{SC})\) and \(\varepsilon_2(\text{M})\) the vanadium dioxide according to the energy \(\omega\) (ev) of the incidental photons \(\varepsilon_2\) is the imaginary part of the VO\(_2\) dielectric function complexes.

We deduce the response of this material through these simulations of the various optical constants: T, R, n, k and CoeffA in the various spectral fields of the I.R to the spectrum visible and to the ultra-violet, respectively.

3. Results
We will simulate by Maple this constant optics in the incidental photon's energy intervals to be able to exploit the optical response of this material in each field of the energy spectrum:

The remote I.R : 0.001242 ≤ \(\omega\) (ev) ≤ 0.04141  
Average I.R : 0.04141 ≤ \(\omega\) (ev) ≤ 0.887  
The close I.R : 0.887 ≤ \(\omega\) (ev) ≤ 1.553  
The visible spectrum : 1.553 ≤ \(\omega\) (ev) ≤ 3.10  
The ultra-violet : 3.10 ≤ \(\omega\) (ev) ≤ 6
4. Discussion

From these simulated curves, we will explain the optical response of this thin layer of the vanadium dioxide at the boundaries of each spectral field using the following schemes:

Scheme 1. Reflectivity and transmittivity expressed as a percentage of VO₂ in the remote infra-red for the energy of the incidental photon ω = 0.001242 ev for the two states, metal and semiconductor.

Scheme 2. Reflectivity and transmittivity expressed as a percentage of VO₂ in the remote infra-red for the energy of the incidental photon ω = 0.04141 ev for the two states, metal and semiconductor.

Scheme 3. Reflectivity and transmittivity expressed as a percentage of VO₂ in the average infra-red for the energy of the incidental photon ω = 0.887 ev for the two states, metal and semiconductor.

Scheme 4. Reflectivity and transmittivity expressed as a percentage of VO₂ in the close infra-red for the energy of the incidental photon ω = 1.553 ev for the two states, metal and semiconductor.

Scheme 5. Reflectivity and transmittivity expressed as a percentage of VO₂ in the visible spectrum for the energy of the incidental photon ω = 3.1 ev for the two states, metal and semiconductor.

Scheme 6. Reflectivity and transmittivity expressed as a percentage of VO₂ in the ultra-violet spectrum for the energy of the incidental photon ω = 6 eV for the two states, metal and semiconductor.

Using this modeling, we notice that:
In remote I.R: 0.001242<ω (ev) < 0.04141:
The VO₂ semiconductor thin layer is enormously transmittive, T ≅ 59% as well as its reflectivity R ≅ 25.6% and the absorptance coeffA ≅ 16%.

• Scheme 1 shows that the VO₂ metal thin layer is very
reflective R ≅ 98%; very weakly transmittive T ≅ 0.16% and less absorbing coeffA ≅ 1, 8% for ω = 0.001242 ev; whereas, scheme 2 indicated, for ω = 0.04141 ev, R ≅ 90% and T ≅ 0.83%; therefore, it remains very reflective and little absorbing coeffA ≅ 9, 93% and very weakly transmittive.

- In the semiconductor state, the vanadium dioxide has a gap of 0.7 ev.

- The energy of the incidental photons is very weak in front of the gap ω ≪ E_g. We notice that T ≅ 59% and R ≅ 25%; hence, the absorptance coeffA ≅ 16%, the vanadium dioxide VO_2 is enormously transmittive, reflective and absorbent. The absorptance is due to the formation of exciton.

- T/R (SC) ≥ 1 whereas T/R (M) ≪ 1; this is explained by the free electron's model of the valence's band in metals.

- Scheme 3 indicates that in the average I.R for ω=0.887 ev:

  - The VO_2 thin layer in the metal state is very reflective R ≅ 70%; whereas, its transmittivity is very weak T = 0.48%, and its absorptance is coeffA ≅ 30%. This is explained by the model of the free electrons.

- For the semiconductor state of VO_2, we note that this thin layer is transmittive, reflective and absorbing because of the electronic transition of the conduction band 3d || towards 3d π (the valence band), since ω > E_g (the energy of the incidental photons is higher than the energy of the gap); this appears clearly in Figure 2.

- The VO_2 metal thin layer remains very reflective, weakly transmittive and absorbing (T ≅ 0.428%, R ≅ 68.45%, coeffA ≅ 31.12%) because for ω<ω_p, the incidental light wave is reflected. In this case, the intensities, the reflective I_r, the absorptive I_a and the transmitted I_t are connected to the incidental intensity I_0 by the following relations:

  \[ I_r \approx 68.45 \% \cdot I_0 \]

  \[ I_a \approx 31.12 \% \cdot I_0 \]

  \[ I_t \approx 0.428 \% \cdot I_0 \]

- The thin layer of VO_2 semiconductor is transmittive, reflective and more absorbing (T ≅ 32.13%, R = 24.43%, coeffA = 43.44%); this is due to the electric transition band-band since ω > E_g.

- Scheme 5 indicates that in the visible spectrum for ω=3.1 ev:

  - The vanadium dioxide in the metal state remains very reflective, weakly transmittive and absorbing (T ≅ 1%, R = 34.55%, coeffA ≅ 64.45%); this is due to the free electrons and also to the ionization of some atoms of the medium which becomes absorbent.

  - The vanadium dioxide semiconductor thin layer is reflective, very weakly transmittive and very absorbing (T ≅ 1%, R ≅ 34.55%, coeffA ≅ 64.45%); we explain this optical response by the electronic transition band-band, starting from the conduction band 3d || towards 3d π since ω>0.7 ev and also of the band 2d π towards 3d π since ω>2.5 ev by using the band structure of the vanadium dioxide semiconductor. The medium becomes ionized and quite absorbing of the incidental beam, and the reflectivity is due to the electronic transition band to band.

- Scheme 6 indicates that in the ultraviolet spectrum for ω=6 ev:

  - The vanadium dioxide in the state metal, is weakly reflective, enormously transmittive and quite absorbing (T ≅ 70.42%, R ≅ 3.81%, coeffA ≅ 38.82%). In this case, the energy of the incidental photons is higher than ω_p=4.47 ev, the incidental light waves are enormously transmitted; whereas, those which are reflective are statistically very weak. The medium behaves as a high-pass filter. It is said that the penetration of these waves in metal is large if ω > ω_p. Even if ω > E_g, the free electrons are attracted towards the oscillating positive charges of this medium which
becomes absorbent. We retain for the VO\textsubscript{2} metal, if \( \omega<\omega_p \), the incidental photons are very reflective (R is high and T is low), it is the case of its optical response in the I.R and the visible spectrum, whereas, in the U.V, because of \( \omega>\omega_p \), it is the transmittivity T which dominates, the reflectivity is low and the absorptance is approximately of 25%.

- The thin layer of the vanadium dioxide in a semiconductor state is reflective and very absorbing (R \( \approx \) 24.30%, coeffA \( \approx \) 75.42%), and almost non-transmittive, because the medium becomes very ionized by the transitions band-band, the electrons of band 3d\textsubscript{||} towards 3d\textsubscript{π} (indeed \( \omega = 6 \) ev, \( E_g = 0.7 \) ev, \( \omega>E_g \)), and those of the band 2d\textsubscript{π} towards 3d\textsubscript{π} (because \( \omega>2.5 \) ev); this is clearly visualized in the band structure of VO\textsubscript{2} in a semiconductor state. The reflectivity is, thus, due to these electronic transitions, and the high absorptance is explained by the ionization of the medium.

- In the infra-red, the vanadium dioxide metal is very reflective (0.7\( \leq R \leq 0.9 \)), whereas its transmittance is very weak (T\( \leq 0.0047 \)). For the semiconductor VO\textsubscript{2}, its transmittivity T is: (0.24\( \leq T \leq 0.27 \)), we notice in this variation that T reaches a maximum and a minimum as it is shown in Figure 3 (e).

Figure 3 (f) indicates that in the ultraviolet beam, the reflectivity of the vanadium dioxide metal decreases with the increase in the energy \( \omega \) of the incidental photons, whereas its transmittivity undergoes a visible and a considerable growth (R \( \geq 0.30 \); T \( \geq 0.70 \) for \( \omega = 6 \) ev). The reflectivity of VO\textsubscript{2} semiconductor decreases from 0.34 up to 0.22 for \( \omega \geq 5.24 \) ev, then it increases slightly towards 0.24 for \( \omega = 6 \) ev, the minimal reflectivity is R\textsubscript{min} = 0.21 for \( \omega \approx 5.42 \) ev.

The variation of the coefficient of extinction k informs us on the evolution of the amplitude of the light wave which is propagated in the vanadium dioxide according to the energy \( \omega \) of the incidental photons in each spectral field. Whereas, the variation of the index of refraction n, according to the energy \( \omega \) of the incidental photons reflects interesting information on the evolution of the phase \( \phi \) of the light wave which is propagated in this material; that is to say in the semiconductor state or metal. We notice an exponential decay of k and n for the VO\textsubscript{2} metal.

| \( \omega \) (ev) | The index of refraction n |
|-----------------|--------------------------|
| 0.001242        | 3.05                     |
| 0.8             | \( n_{\text{min}} = 2.87 \) |
| 1.57            | \( n_{\text{max}} = 3.17 \) |
| 2.684           | \( n_{\text{min}} = 3.39 \) |
| 4.824           | \( n_{\text{max}} = 1.90 \) |
| 6               | 2.40                     |

| \( \omega \) (ev) | The coefficient of extinction k |
|-----------------|--------------------------------|
| 0.001242        | 2.56                          |
| 1.628           | \( k_{\text{min}} = 0.51 \)   |
| 1.84            | \( k_{\text{max}} = 0.41 \)   |
| 3.678           | \( k_{\text{min}} = 1.765 \)  |
| 5.64            | \( k_{\text{max}} = 1.014 \)  |
| 6               | 1.065                         |
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Figure 4. (c) The variation of the indexes of refraction \(n(SC)\) and \(n(M)\) the vanadium dioxide according to the energy \(\omega\) (ev) of the incidental photons. (d) The variation of the coefficient of extinction \(k(SC)\) and \(k(M)\) the vanadium dioxide according to the energy \(\omega\) (ev) of the incidental photons.

In the energy interval of the incidental photons \(0.001242 \leq \omega\) (ev) \(\leq 6\), we note that the coefficient of extinction \(k\) is characterized by two minima and two maxima as it is the case of the index of refraction \(n\).

Our simulation results of various vanadium dioxide optical constants \((n, k, R \text{ and } T)\) are closer to the works of\(^{11}\) thus, they are in conformity with different optical theories of the semiconductors and metals.

For the simulation of the CoffA absorptance we notice that the model of Lorentz of seven oscillators provides more information on this coefficient in the case of the vanadium dioxide semiconductor in comparison with the same model of four oscillators while, for the \(\text{VO}_2\) metal, the Drude’s model also describes this optical property as shown in Figures 5, 6, 7, 8. This information is summarized in the following Table 4.

Table 4. The maximum and minimum of coeffA optical absorbtance in the semiconductor and metal states of \(\text{VO}_2\) thin layer for the \(\omega\) energy of the incidental photon

\[
\begin{array}{ccccccc}
\text{VO}_2\text{ (semiconductor)} & \text{VO}_2\text{ (metal)} \\
\text{Lorentz’ model} & \text{Drude’s model} & \text{Lorentz’ model} & \text{Drude’s model} & \text{Lorentz’ model} & \text{Drude’s model} \\
\hline
\text{7 Oscillators} & \text{4 Oscillators} & \text{1 Oscillator} & \text{4 Oscillators} & \text{1 Oscillator} & \text{4 Oscillators} & \text{1 Oscillator} \\
\text{CoeffA (Max)} & \text{CoeffA (Min)} & \text{CoeffA (Max)} & \text{CoeffA (Min)} & \text{CoeffA (Max)} & \text{CoeffA (Min)} \\
0.783; \omega = 5.4 \text{ ev} & 0.641; \omega = 3.49 \text{ ev} & 0.738; \omega = 2.954 \text{ ev} & 0.5016; \omega = 1.93 \text{ ev} & 0.52637 & 0.0183; \omega = 0.001242 \text{ ev} \\
0.6441; \omega = 3.197 \text{ ev} & 0.436; \omega = 1.748 \text{ ev} & 0.543; \omega = 1.463 \text{ ev} & 0.0817; \omega = 0.001242 \text{ ev} & \omega = 4.401 \text{ ev} & \omega = 0.001242 \text{ ev} \\
0.4392; \omega = 1.4497 \text{ ev} & 0.15169; \omega = 0.001242 \text{ ev} & & & & \\
\end{array}
\]

Figure 5. (g) The variation of the absorptance coeffA according to the energy \(\omega\) (ev) of the incidental photons for the \(\text{VO}_2\) semiconductor (SC), 4 and 7 oscillators and for the \(\text{VO}_2\) metal (M) in the remote infra-red.

Figure 6. (h) The variation of the absorptance coeffA according to the energy \(\omega\) (ev) of the incidental photons for the \(\text{VO}_2\) semiconductor (SC), 4 and 7 oscillators and for the \(\text{VO}_2\) metal (M) in the average infra-red.
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Figure 7. (i) The variation of the absorptance coeffA according to the energy $\omega$ (ev) of the incidental photons for the VO$_2$ semiconductor (SC), 4 and 7 oscillators and for the VO$_2$ metal (M) in the close infra-red.

In the ultraviolet beam, for $\omega = 6$ ev, the vanadium dioxide metal absorbs approximately 0.2576; whereas this semiconductor material, if we use the model of Lorentz of four oscillators, roughly absorbs 0.26; and in the case of Lorentz’ model of seven oscillators, we have an absorptance of approximately 0.754.

The maximum of CoeffA of the vanadium dioxide metal is obtained for the frequency of the incidental photons which is practically equal to the plasma frequency $\omega_p$. From this maximum, the absorptance decreases and the transmittance increases.

5. Conclusion

This work summarizes the evolution and the comparison of the optical functions of the vanadium dioxide in the two states- semiconductor and metal- and especially the CoeffA absorptance, by using the transmittance and the reflectivity of this thin layer. This general study allows the incorporation of this intelligent material in various technological nano applications, like the solar air-conditioners and the thermal pumps.

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Figure 8. (j) The variation of the absorptance coeffA according to the energy $\omega$ (ev) of the incidental photons for the VO$_2$ semiconductor (SC) 4 oscillators. (k) the variation of the absorptance coeffA according to the energy $\omega$ (ev) of the incidental photons for the VO$_2$ semiconductor (SC) 7 oscillators. (l) The variation of the absorptance coeffA according to the energy $\omega$ (ev) of the incidental photons for the VO$_2$ metal (M).
7. References

1. Cavalleri A, Dekorsy T, Chong HHW, Kieffer JC, Schoenlein RW. Evidence for a structurally-driven insulator-to-metal transition in VO₂: A view from the ultrafast timescale. Physical Review B. Int. American Physical Society (APS). 2004 Oct 13; 70(16):1–17.

2. Morin FJ. Oxides which show a metal-to-insulator transition at the neel temperature. Physical Review Letters American Physical Society (APS). 1959 Jul 1; 3(1):34–6.

3. Paradis, Suzanne. Étude du VO₂ déposé par pulvérisation magnétron RF comme matériau fonctionnel pour la commutation IR. Recherche et développement pour la défense Canada; 2006. p. 2005–375.

4. Gmelin Handbook. Section Vanadium Oxides. 1990; 16:482.

5. Xiao D, Kim KW, Zavada JM. Imaging properties of a metallic photonic crystal. Journal of Applied Physics. AIP Publishing. 2007; 101(11):113–05.

6. Golubev VG, Davydov VY, Kartenko NF, Kuryukov DA, Medvedev AV, Pevtsov AB. Phase transition-governed opal–VO₂ photonic crystal. Applied Physics Letters. AIP Publishing. 2001; 79(14):21–7.

7. Kim HT, Chae BG, Youn DH, Maeng SL, Kim G, Kang KY. Mechanism and observation of Mott transition in VO₂-based two- and three-terminal devices. New J Phys. IOP Publishing. 2004 May 18; 6:52–2.

8. Deep GS. Modeling of the hysteretic metal-insulator transition in a vanadium dioxide infrared detector. Opt Eng SPIE-Intl Soc Optical Eng. 2002 Oct 1; 41(10):2582–8.

9. Zhou J, Gao Y, Zhang Z, Luo H, Cao C, Chen Z, et al. VO₂ thermochromic smart window for energy savings and generation. Scientific Reports. Nature Publishing Group. 2013 Oct 24; 3.

10. Berger M. Porosity of nanocoating improves ‘smart’ window performance. Available from: http://www.nanowerk.com/spotlight/spotid=23840.php

11. Verleur HW, Barker AS, Berglund CN. Optical properties of VO₂ between 0.25 and 5 eV. Physical Review. American Physical Society (APS). 1968 Aug 15; 172(3):788–98.

12. Mossannek RJO, Abbate M. Optical response of metallic and insulating VO₂ calculated with the LDA approach. Journal of Physics: Condens Matter. IOP Publishing. 2007 Jul 26; 19(34):346225.

13. Kakiuchida H, Jin P, Nakao S, Tazawa M. Optical properties of vanadium dioxide film during semiconductive–metallic phase transition. Japanese Journal of Applied Physics. Japan Society of Applied Physics. 2007 Jan 26; 46(5):113–6.

14. Lorentz HA. The motion of electrons in metallic bodies. I Proceedings Koninklijke Akademie van Wetenschappen. 1905; 7:438–53.

15. Lorentz HA. The motion of electrons in metallic bodies. II Proceedings Koninklijke Akademie van Wetenschappen. 1905; 7:585–93.

16. Lorentz HA. The motion of electrons in metallic bodies. III Proceedings Koninklijke Akademie van Wetenschappen. 1905; 7:684–91.

17. Drude P. Zur Elektronentheorie der Metalle. Annalen der Physik. Wiley-Blackwell. 1900; 308(11):369–402.

18. Drude P. Zur Elektronentheorie der Metalle; II. Teil Galvanomagnetische und thermomagnetische Effecte. Annalen der Physik. Wiley-Blackwell. 1900; 308(11):369–402.

19. Kana JBK, Ndjaka JM, Vignaud G, Gibaud A, Maaza M. Thermally tunable optical constants of vanadium dioxide thin films measured by spectroscopic ellipsometry. Optics Communications. Elsevier BV. 2011 Feb; 284(3):807–12.

20. Benchaib A, Mdaa A, Zorkani I, Jorio A. Optical properties of the Vanadium dioxide. Journal of Advances in Physics. 2015; 8(2):2148–55.

21. Benchaib A, Mdaa A, Zorkani I, Jorio A. Optical properties of a thin layer of the Vanadium dioxide at the metal state. Journal of Advances in Physics. 2015; 9(1):2303–10.

22. kianfar E. Production and identification of vanadium oxide nanotubes. Indian Journal of Science and Technology. 2015 May; 8(S9):455–64.

23. Kathirvelu S, D’Souza L, Dhurai B. A comparative study of multifunctional finishing of cotton and P/C blended fabrics treated with titanium dioxide/zinc oxide nanoparticles. Indian Journal of Science and Technology. 2008 Dec; 1(7):1–12.