Research Article

Information Restitution in the Optical Memories using a Thin Layer of the Vanadium Dioxide

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Abstract

Today, nanotechnologies have become a very important part of our daily life, contributing to the significant improvement of many technological and industrial sectors such as information technology, internal security, medicine, transport, energy, food safety, environmental sciences and many others. This technology allows materials to be processed at the nanoscale. We have studied the vanadium dioxide VO2, a material that is currently being researched in the development of new technologies, and the possibility of integrating nanoparticles of this material into the energy field, knowing that it's considered an intelligent material. Each cooling followed by heating of such a material generates a hysteresis loop, the area of this loop represents the energy dissipated in this material. In this paper, we will mathematically model this loop to determine the dissipated energy E that can be reduced or reused as an energy source. We compared the energy dissipated in pure vanadium dioxide and doped according to the two types of doping n-type with 5% tungsten (W), p-type with 15% chromium (Cr), we find that doping in general results in a decrease in the energy dissipated in this material compared to the pure state.

Keywords: High speed circuits, Right angle bend, FDTD and MNA methods, Eye Diagram, noisy CMOS.

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1. Introduction

In the context of scientific and technological change, nanotechnology has become the main research focus of all researchers. Many benefits of nanotechnology depend on the ability to adapt material structures to scales below 100 nanometers to obtain nanomaterials that are composed of nanoparticles, which greatly expands the concepts of materials science. These nanoparticles are included as nano additives in different fields. The titanium dioxide nanoparticles TiO_2, in the sunscreens [1], the nanoparticles in the food packaging [2]; the zinc oxide nanoparticles ZnO, in the sunscreens, in the exterior coatings, and in the paintings [1,3]; the cerium oxide nanoparticles CeO_2 [4,5] acting as catalyst for the fuels.

This gives rise to new discoveries such as intelligent materials, there are particularly materials that have the ability to receive information from their environment and interact with this environment by changing their properties (optical, electrical, mechanical, etc.) following the external stimuli. The vanadium dioxide VO_2 was discovered over 50 years ago by F. J. Morin [6], that highlighted its reversible phase transition [7-13] from the semiconductor state to its metallic state at a transition temperature of $\theta_t = 68°C$.

This phase transition causes enormous changes in the optical and electrical properties of this material [14-18] in the near infrared. Below the transition temperature the resistivity [19] decreases exponentially as the temperature

increases. At the temperature $\theta_t = 68°C$, the resistance abruptly falls with three orders of magnitude. Beyond 90°C, the resistivity is stabilized in 0.05 Ωcm. In the infra-red, the optical constants undergo a definitely distinguished variation like the transmittivity T [20,21]. In this context, we observe a significant variation in the transmittivity of the VO_2 film between the insulating state characterized by a high transmittivity (42% at 5°C) and the metallic state, where the transmittivity is very low (5% at 100°C).

This transition is effected in a very short time, in the order of a few nanoseconds. Below θ_t ($\theta < 68°C$), the VO_2 behaves as an insulator with a monoclinic crystalline structure where we have an alternation of the short v-v (2.65 Å) and long (3.12 Å) bonds; this led to a doubling of the parameter c and the opening of the gap [22,23], in the conduction band 3d of the vanadium [24] and a high transmittivity, but above θ_t ($\theta > 68°C$), the material is suddenly transformed and acquires the behaviour of a metal with a rutile tetragonal quadratic structure, characterized by octahedra chains VO_6 [25], joined by the peaks along the axis c with distances $d_{v-v} = 2.88$ Å and a low transmittivity. In order to introduce this application in everyday life, it's necessary to lower the critical temperature θ_t of vanadium dioxide by doping it with different elements [26-30]. Indeed, the doping of a thin layer of VO_2 with different doses of tungsten W [31] lowers the transition temperature to around 28°C.

In the infrared spectrum, during heating and cooling of this material, a hysteresis loop appeared. In physics, a hysteresis loop represents a quantity of energy dissipated [8,15] in this material by traversing this loop completely or partially. We will try to make a mathematical modeling of

the optical hysteresis loop [32,33], throughout the phase transition VO$_2$ (semiconductor) $\rightleftarrows$ VO$_2$ (metal), during a heating followed by a cooling between the temperatures $\theta_1 = 30°C$ and $\theta_2 = 100°C$ or between $\theta_1 = 30°C$ and θ_i such as $\theta_1 < \theta_i < \theta_2$.

In this study, we simulated and analyzed the energy dissipated in pure and doped state with 5% W and 15% Cr [34] of vanadium dioxide, which makes this material a promising candidate in various fields. In computing; the use of this dissipated energy as a means of increasing the speed of data storage in optical memories and storage masses. In the energy field; the use of vanadium dioxide nanoparticles as nano additives in fuels to reduce the energy dissipated by combustion.

2. Method

We have based on the bibliographic results referenced by [31,34], concerning the study of the transmittivity T of a thin layer of vanadium dioxide.

According to Fig.1, we modelled the mathematical expression of the transmittivity T for the pure and doped state (5% W and 15% Cr) of vanadium dioxide in different temperature intervals θ.

In the pure state of VO$_2$, for a temperature of 5°C $<\theta<$ 30°C, the transmittivity expression T, in heating and cooling is:

$$\begin{cases} T = a\theta + C_1 \\ a \to 0 \; ; \; C_1 = cste \end{cases}$$

For a temperature of 5°C $< \theta <$ 30°C the transmittivity is constant and takes the value $T = C_1 = 40.3$ %

When the temperature interval boundaries $\theta_1 < \theta < \theta_2$ takes the values $\theta_1 = 30°C$ and $\theta_2 = 100°C$, the transmittivity curve T becomes exponential, and the mathematical expressions T in heating and cooling are:

While heating:

$$\begin{cases} T_1 = A \exp(-b_1\theta) \\ b_1 = cste > 0 \; ; \; A = cste \end{cases}$$

While cooling:

$$\begin{cases} T_2 = B \exp(-b_2\theta) \\ b_2 = cste > 0 \; ; \; B = cste \end{cases}$$

A, B, b_1 et b_2 are constants which we can graphically determine, starting from the curve of hysteresis: A = 4.100765 % ; B = 3.956749 % ; b_1 = 0.040547(°C)$^{-1}$; b_2 = 0.0532(°C)$^{-1}$.

For the doped state of VO$_2$ by 5% W, the temperature boundaries $\theta_1 < \theta < \theta_2$, takes the values $\theta_1 = 5°C$ and $\theta_2 = 65°C$, and the mathematical expressions T in heating and cooling are:
While heating:

$$\begin{cases} T_1 = A \exp(-b_1\theta) \\ b_1 = cste > 0 \; ; \; A = cste \end{cases}$$

While cooling:

$$\begin{cases} T_2 = B \exp(-b_2\theta) \\ b_2 = cste > 0 \; ; \; B = cste \end{cases}$$

Where,
A = 0.508193 %; B = 0.543532 %; b_1 = 0.033509 (°C)$^{-1}$; b_2 = 0.04621 (°C)$^{-1}$

For the doped state of VO$_2$ by 15% Cr, the temperature boundaries $\theta_1 < \theta < \theta_2$, takes the values $\theta_1 = 53°C$ and $\theta_2 = 117°C$, and the mathematical expressions T in heating and cooling are:
While heating:

$$\begin{cases} T_1 = A \exp(-b_1\theta) \\ b_1 = cste > 0 \; ; \; A = cste \end{cases}$$

While cooling:

$$\begin{cases} T_2 = B \exp(-b_2\theta) \\ b_2 = cste > 0 \; ; \; B = cste \end{cases}$$

Where,
A = 4.045339 % ; B = 16.135495 % ; b_1 = 0.036154 (°C)$^{-1}$; b_2 = 0.048012 (°C)$^{-1}$

We calculate the surface I ranging between two curves 1 and 2 of the hysteresis loop in the VO$_2$ material during this variation of up-and-down as shown in scheme 1, by the equation (1):

$$|I| = \frac{E_{dissipated}}{h\nu} = \frac{E_{dissipated}}{\hbar\omega} \tag{1}$$
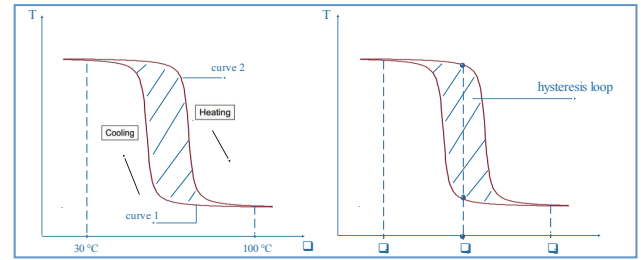
Scheme. 1 The variation of the transmittivity T of a thin layer of the vanadium dioxide with the hysteresis loop

we pose:

$$I_1 = \int_{\theta_1}^{\theta_2} T_1 d\theta \; ; \; I_2 = \int_{\theta_2}^{\theta_1} T_2 d\theta \tag{2}$$

$$I = I_2 - I_1 \tag{3}$$

Thus:

$$I = -\int_{\theta_1}^{\theta_2} T_1 d\theta + \int_{\theta_2}^{\theta_1} T_2 d\theta \tag{4}$$

$$I = -\int_{\theta_1}^{\theta_2} A \exp(-b_1\theta) d\theta - \int_{\theta_1}^{\theta_2} B \exp(-b_2\theta) d\theta$$

$$I = \frac{A}{b_1}[\exp(-b_1\theta)]_{\theta_1}^{\theta_2} + \frac{B}{b_2}[\exp(-b_2\theta)]_{\theta_2}^{\theta_1}$$

$$I = \frac{A}{b_1}(\exp(-b_1\theta_2) - \exp(-b_1\theta_1))$$
$$+ \frac{B}{b_2}(\exp(-b_2\theta_2) - \exp(-b_2\theta_1))$$

$$I = \frac{A}{b_1}\left(e^{-b_1\theta_2} - e^{-b_1\theta_1}\right) + \frac{B}{b_2}\left(e^{-b_2\theta_2} - e^{-b_2\theta_1}\right) \quad (5)$$

The dissipated energy in this material during this hysteresis loop is:

$$E_{dissipated} = |I| \cdot h\nu \quad (6)$$

For $\theta_1 < \theta_i < \theta_2$,

$$\begin{cases} 30°C < \theta_i < 100°C \text{ for pure } VO_2 \\ 5\ °C < \theta_i < 65°C \text{ for } W-\text{doped } VO_2 \\ 53\ °C < \theta_i < 117°C \text{ for } Cr-\text{doped } VO_2 \end{cases}$$
$$E_{dissipated} = |I'_2 - I'_1| \cdot h\nu,$$

Where:

$$I'_1 = \int_{\theta_1}^{\theta_i} T_1 d\theta \; ; \; I'_2 = \int_{\theta_2}^{\theta_i} T_2 d\theta \quad (7)$$

$$I' = I'_2 - I'_1 \quad (8)$$

$$I'_1 = \int_{\theta_1}^{\theta_i} A\exp(-b_1\theta)d\theta \; ; \; I'_2 = \int_{\theta_2}^{\theta_i} B\exp(-b_2\theta)d\theta$$

$$I'_1 = -\frac{A}{b_1}[\exp(-b_1\theta)]_{\theta_1}^{\theta_i} \; ; \; I'_2 = -\frac{B}{b_2}[\exp(-b_2\theta)]_{\theta_2}^{\theta_i}$$

$$I'_1 = -\frac{A}{b_1}(\exp(-b_1\theta_i) - \exp(-b_1\theta_1)) \; ; \; I'_2$$
$$= -\frac{B}{b_2}(\exp(-b_2\theta_i) - \exp(-b_2\theta_2))$$
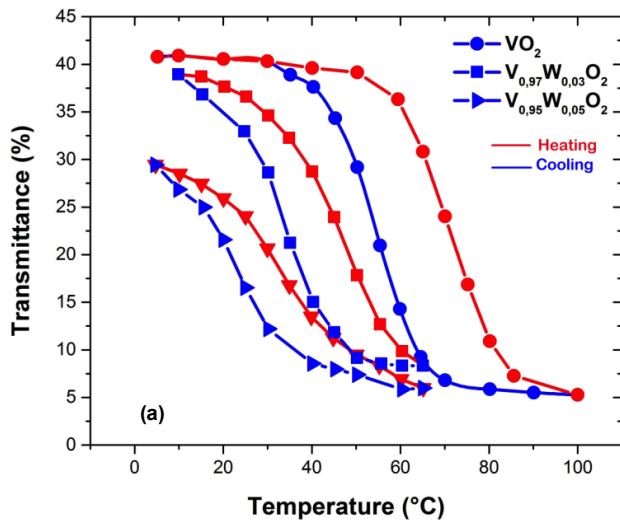
$$I' = \frac{A}{b_1}(\exp(-b_1\theta_i) - \exp(-b_1\theta_1))$$
$$- \frac{B}{b_2}(\exp(-b_2\theta_i) - \exp(-b_2\theta_2)) \quad (9)$$

$$E_{dissipated} = h\nu \cdot \left| \frac{A}{b_1}(\exp(-b_1\theta_i) - \exp(-b_1\theta_1)) \right.$$
$$- \frac{B}{b_2}(\exp(-b_2\theta_i)$$
$$\left. - \exp(-b_2\theta_2)) \right| \quad (10)$$

We see that the dissipated energy $E_{dissipated}$ in the vanadium dioxide depends on two parameters: the frequency ν of the incidental photons and the temperature θ.

From the expression of the dissipated energy $E_{dissipated}$, we can extract the variation from the transmittivity T according to θ for a fixed frequency ν.

3. Results & Discussion

According to this mathematical modeling of the functions which limit this optical hysteresis loop concerning the variation of the transmittivity T as function of the temperature θ, we can calculate the dissipated energy E in a thin layer of the pure and W-doped or Cr-doped vanadium dioxide [31,34], in the infra-red spectrum for a frequency ν or determined energy $\hbar\omega$, by completely or partially traversing this hysteresis loop as shown in Fig. 1. We note that the transmittivity T of this thin layer of pure and VO_2 doped varies in exponential decreasing between the bounds of hysteresis but in an irreversible way during a heating followed by a cooling and reciprocally; this produced a dissipated energy in this material.
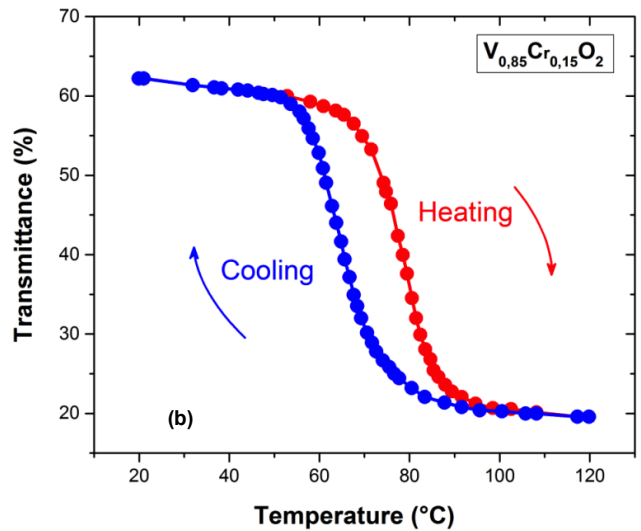
Fig. 1 Transmittivity of a thin layer of the vanadium dioxide during the heating and cooling for $\lambda=2000$nm. (a) W-doped VO_2 by Batista et al. [31]. (b) Cr-doped VO_2 by Beteille and Livage [34].

By fixing the frequency ν in the infra-red and by varying the temperature θ as shown in Figs. 2, 3, 4 and 5; we deduce that the energy dissipated in the VO_2 intrinsic and the VO_2 doped type n by 5% W increases if the temperature θ is increasing; this result allows us to see the decrease of the amplitude of the transmittivity T and to envisage the transition phase of this thin layer from the semiconductor state to the metal state and reciprocally. This dissipated energy also enables us to consult the deferent electronic transitions in the semiconductor state since it is related to light energy $\hbar\omega$ of the incidental photons for the given temperatures, and it causes the excitation of the electrons of the energy bands of pure VO_2 on the one hand, and for the W- doped VO_2, on the other hand, we can control the increase of this dissipated energy as a function of temperature. In the infra-red, this dissipated energy E in this hysteresis loop can be converted into other forms of energy which will become useful, such as the optical memories or

the storage mass, the detectors of the infra-red, the solar-water heaters, where it is used for the temperatures of the pumps release which helps circulate the fluids in the thermal networks.
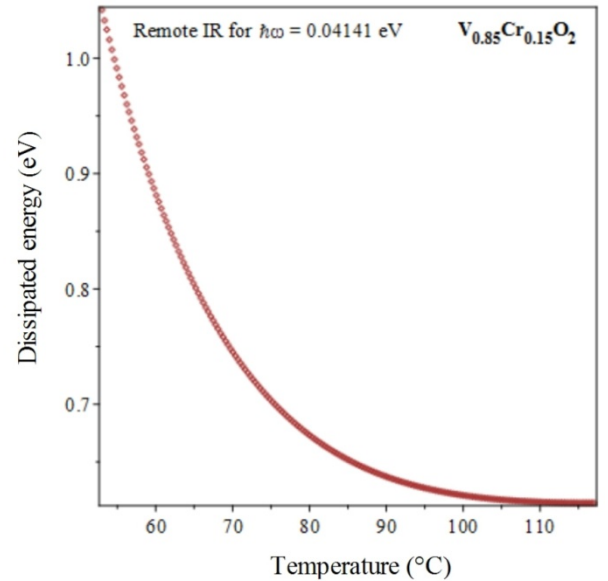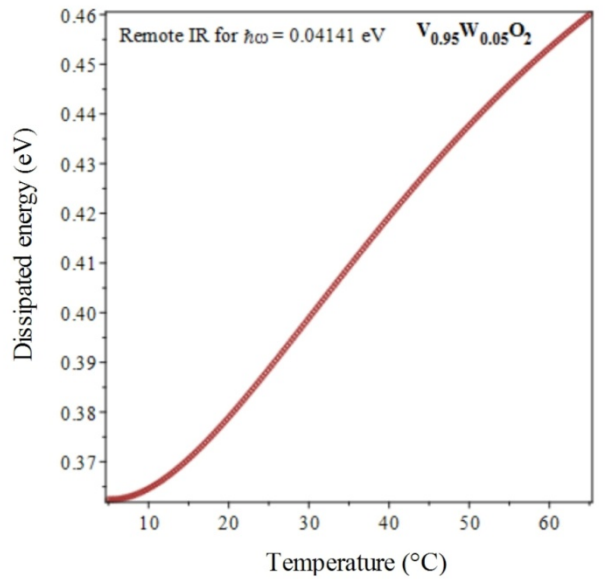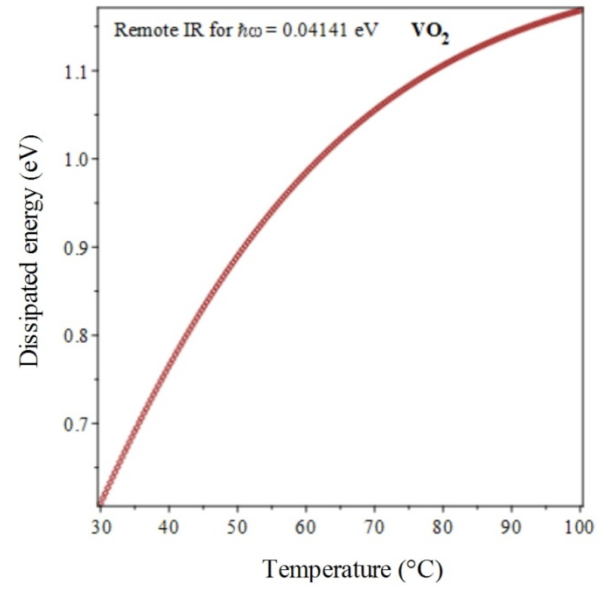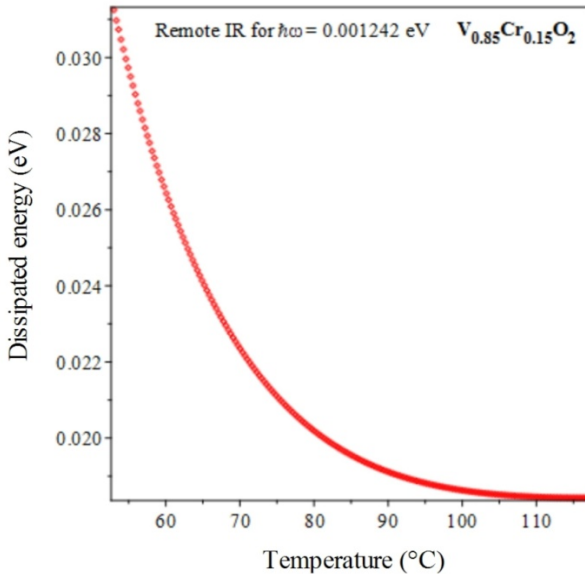

Fig. 2 The dissipated energy according to the temperature in the remote infra-red for $\hbar\omega = 0.001242$ eV
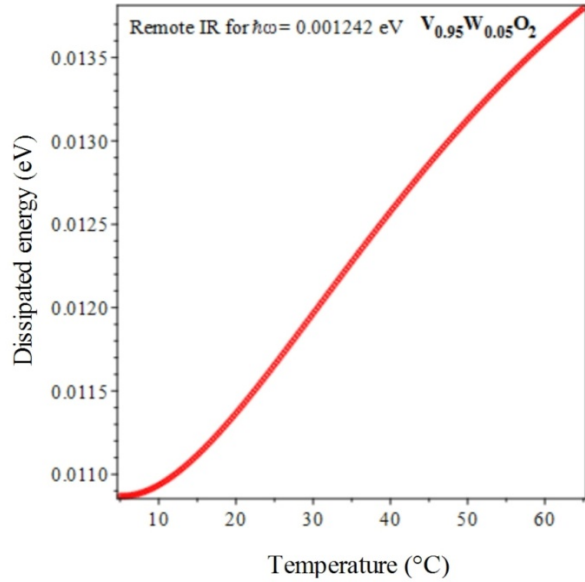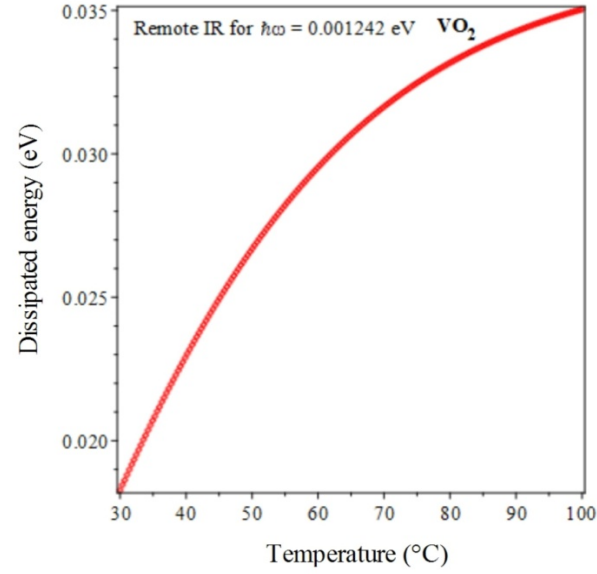
Fig. 3 The dissipated energy according to the temperature in the remote infra-red for $\hbar\omega = 0.04141$ eV.
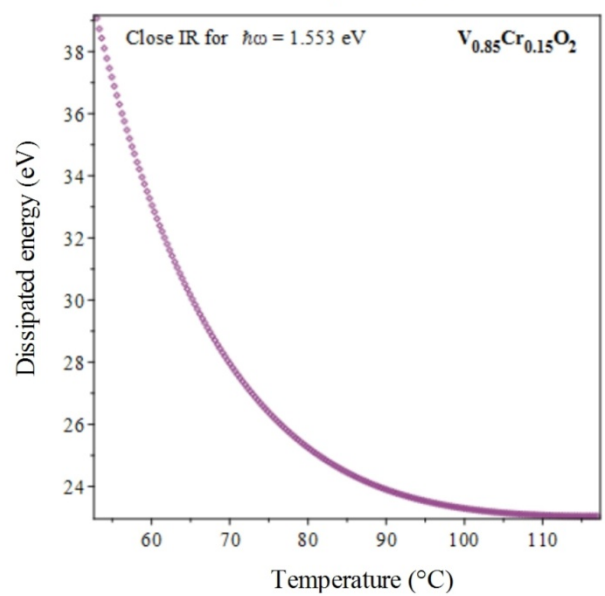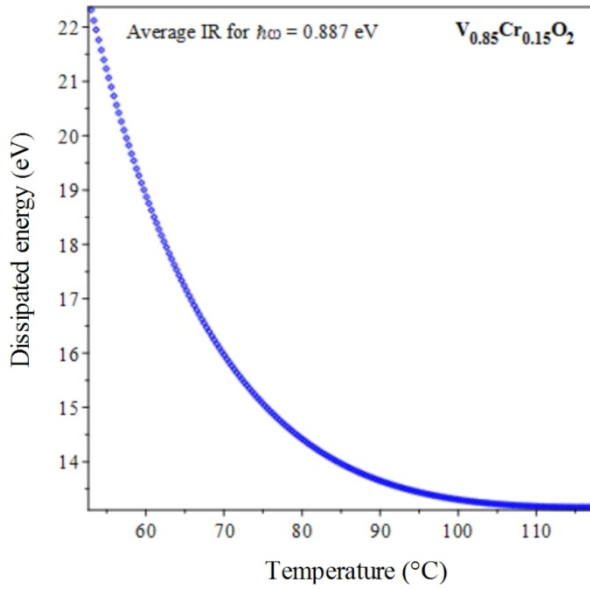
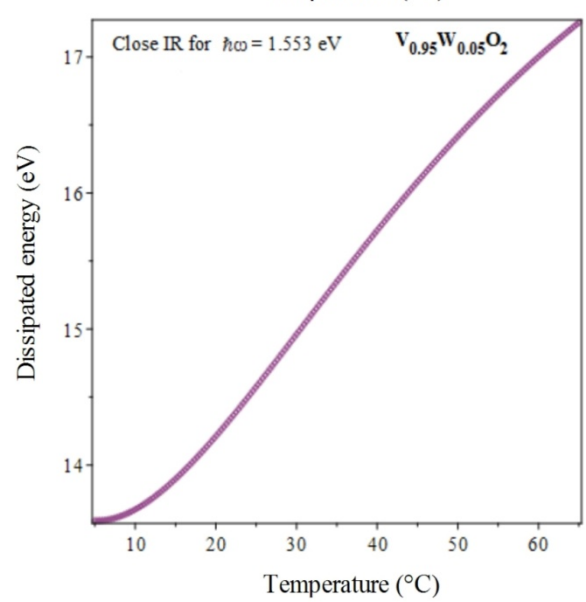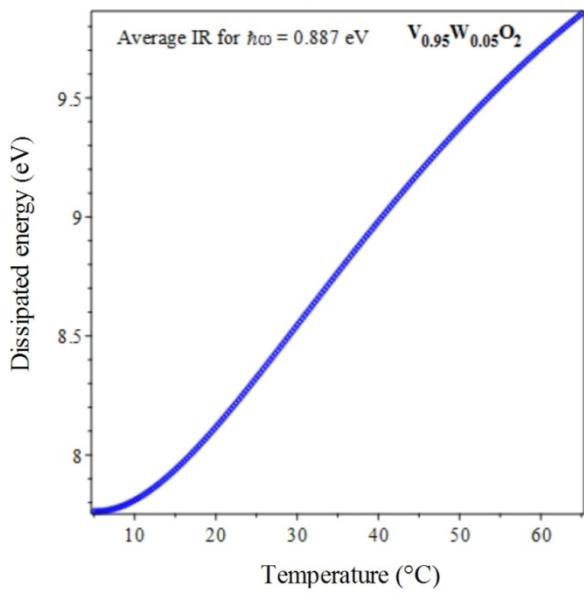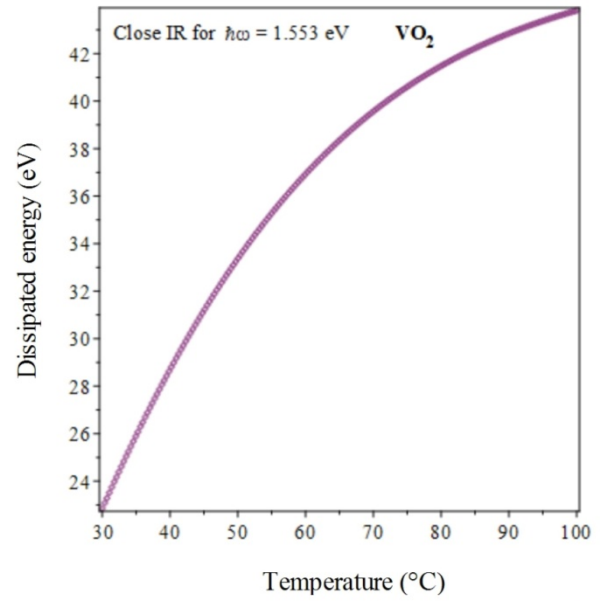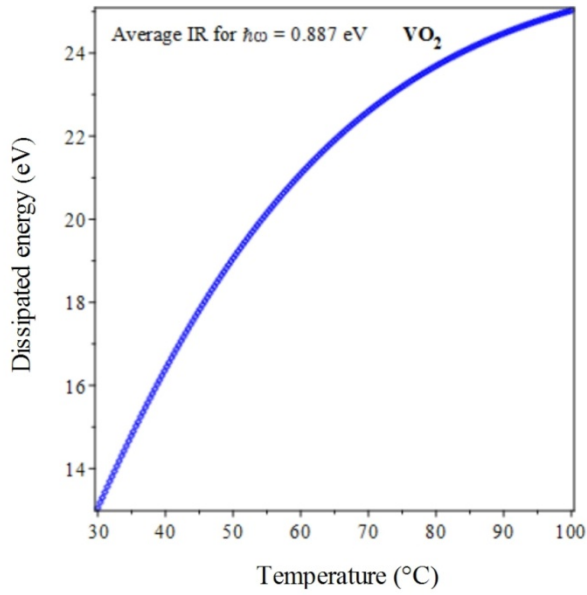**Fig. 4** The dissipated energy according to the temperature in the average infra-red for ℏω = 0.887 eV

Fig. 5 The dissipated energy according to the temperature in the close infra-red for ℏω = 1.553 eV.

In the case of the p-type doping of VO_2 by 15% Cr, there is an exponential decrease in the energy dissipated in this

material due to the excess of the holes caused by this type of doping. It can be introduced in applications such as commutators, transistors.

If we carry out a frequency of 50 or 1000 times or more of this hysteresis loop concerning the transmittivity T of this thin layer of VO₂, we notice that the dissipated energy E becomes important in value which we can transform according to our utilities or special needs. Therefore, it is necessary to know how and to be able to calculate this dissipated energy in this material during a thermochromic phase transition.

According to the uncertainty principle of Heisenberg [35], $\Delta E \cdot \Delta t \cong \hbar/2$ or $\Delta x \cdot \Delta p \cong \hbar/2$, this energy can be dissipated in the optical memories (or the storage mass) of the thin layer of the pure or doped vanadium dioxide so as to be able to calculate the time Δt of the information storage. Indeed, if the energy ΔE is weak then Δt is large and conversely. This is realizable in the infra-red spectrum, as it is shown in Tables.1, 2, and 3 which are extracted respectively of Figs. 6, 7 and 8. We note that the restitution time Δt increases by n-type doping, while the p-type doping does not have a great influence on this time
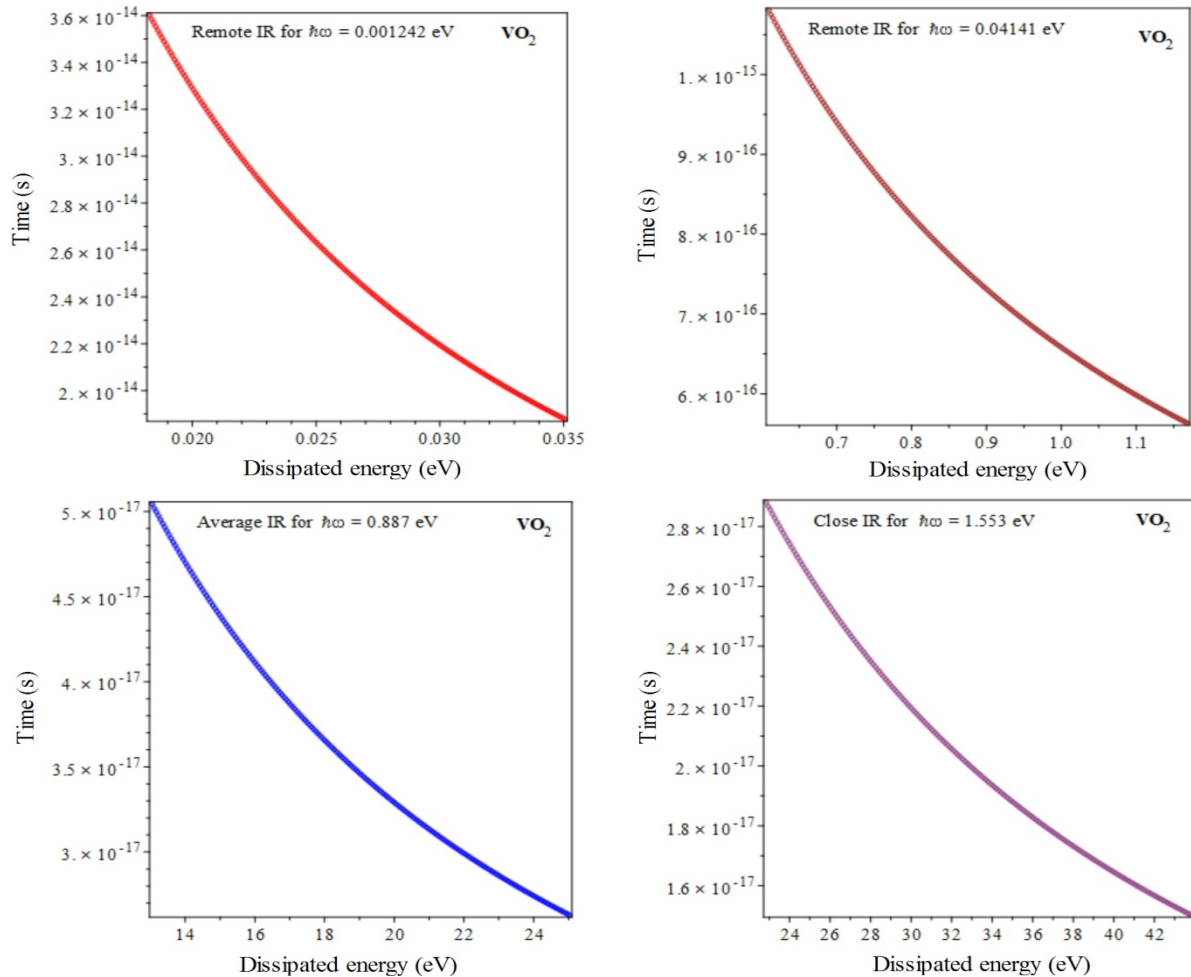

Fig. 6 Variation of the time of storage Δt according to the energy dissipated in the infra-red for pure VO₂.

Table 1.Some values of the storage time according to the energy dissipated in the I.R for pure VO₂

Energy of the photon in the I.R ω (eV)	Dissipated energy E (eV)	Storage time Δt (ns)
0.001242	0.034	$2 \cdot 10^{-5}$
0.04141	1.15	$5.6 \cdot 10^{-7}$
0.887	25	$2.6 \cdot 10^{-8}$
1.553	43	$1.5 \cdot 10^{-8}$

Table 2.Some values of the storage time according to the energy dissipated in the I.R for W-doped VO₂

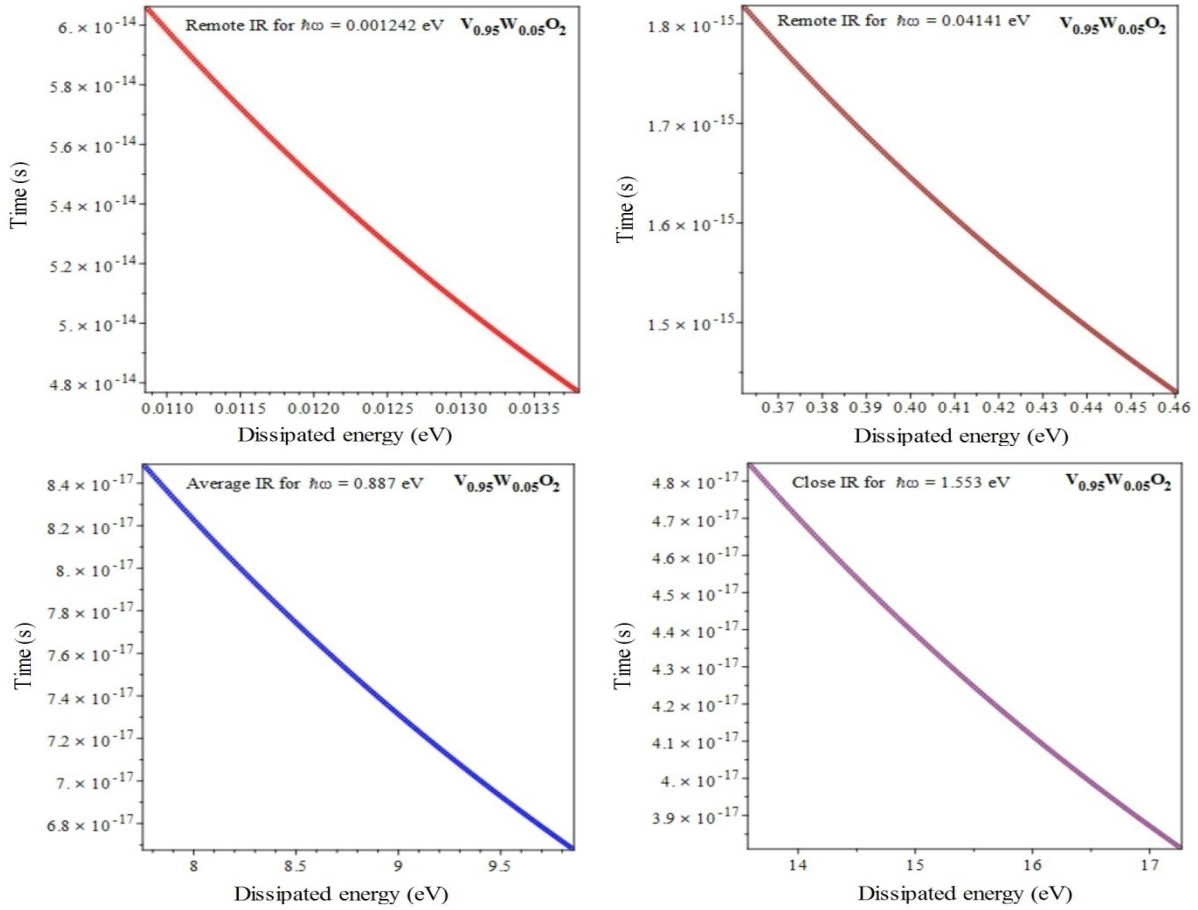| Energy of the photon in the I.R ω (eV)	Dissipated energy E (eV)	Storage time Δt (ns)
0.001242	0.013	$4.77 \cdot 10^{-5}$
0.04141	0.46	$1.43 \cdot 10^{-6}$
0.887	9.85	$6.68 \cdot 10^{-8}$
1.553	17.25	$3.81 \cdot 10^{-8}$

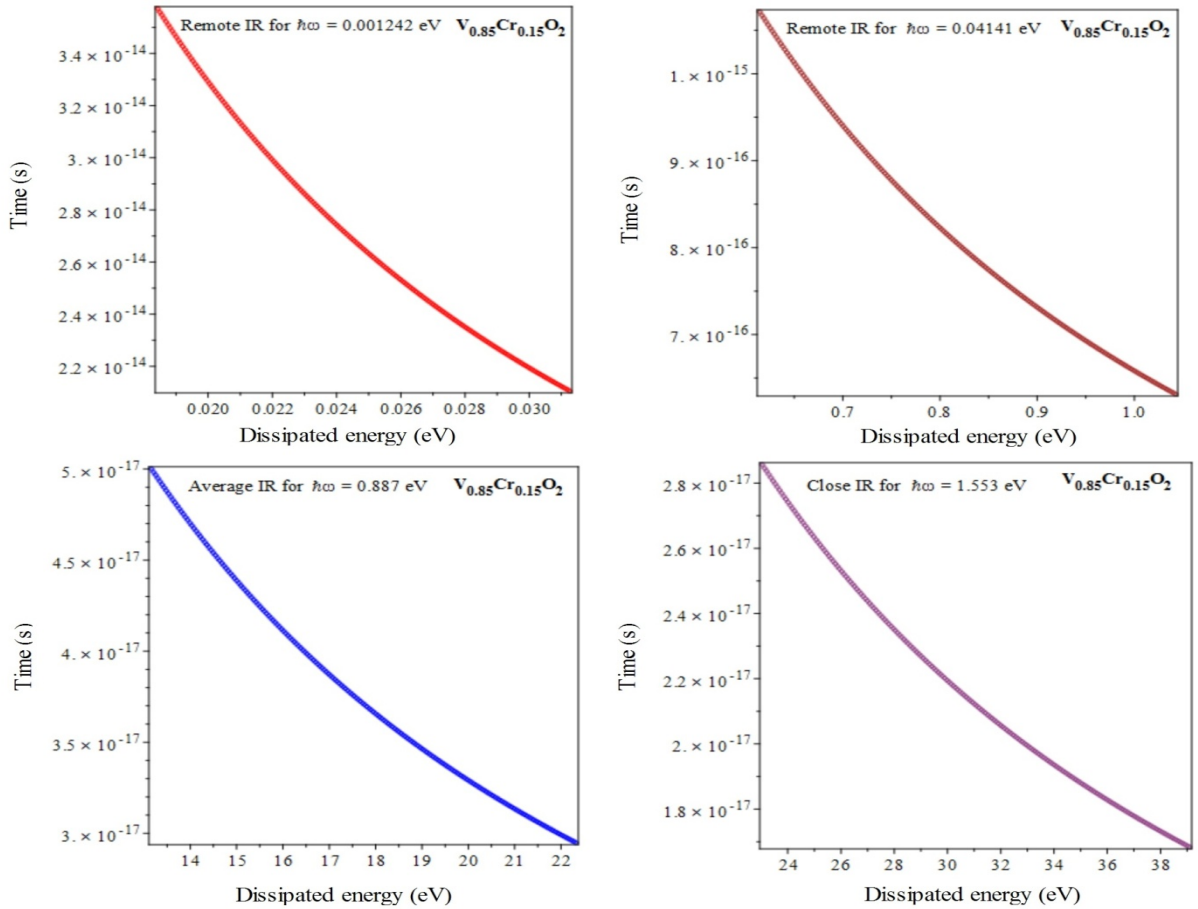**Fig. 7** Variation of the time of storage Δt according to the energy dissipated in the infra-red for W-doped VO₂.

Fig. 8 Variation of the time of storage Δt according to the energy dissipated in the infra-red for Cr-doped VO₂.

Table 3.Some values of the storage time according to the energy dissipated in the I.R for Cr-doped VO_2

Energy of the photon in the I.R ω (eV)	Dissipated energy E (eV)	Storage time Δt (ns)
0.001242	0.032	$2.1 \cdot 10^{-5}$
0.04141	1.041	$6.32 \cdot 10^{-7}$
0.887	22.31	$3 \cdot 10^{-8}$
1.553	39.07	$1.68 \cdot 10^{-8}$

We note that the doping of a thin layer of VO_2 decreases the transmittivity. The area of the hysteresis loop decreases by the tungsten W-doped VO_2 film, which makes it possible to increase the storage time Δt of the information in the storage masses.

For VO_2 tungsten doping, it can be seen that the dissipated energy increases as the incident photons' energy increases in the infrared, and for each area of the I.R, we have:

$$\frac{\Delta t(\text{ W} - \text{doped VO}_2)}{\Delta t(\text{pure VO}_2)} \cong 2.5$$

In this study, we noted that the storage time t in a W-doped vanadium dioxide thin film is a multiple of the storage time in a pure vanadium dioxide thin film by a factor of about 2.5.

For the Cr-doped VO_2, we find that this time Δt is of the same order of magnitude as that of pure VO_2.

4. Conclusion

This study focuses on an intelligent material characterized by these thermochromic properties, namely the vanadium dioxide. A cooling operation followed by heating of this material is expressed by a hysteresis loop. The area of this loop represents the energy dissipated in this material. To facilitate the understanding of this phenomenon, we have mathematically modelled this energy dissipated in this material in pure and doped state (5%W and 15%Cr). The results obtained showed that the doping of vanadium dioxide

n-type or p-type reduces the energy dissipated compared to the pure state of this material. When the doping is n-type, the energy dissipated increases as the temperature increases in the infrared spectrum, due to electronic mobility in this material. While the doping is p-type, the energy dissipated decreases compared to the pure state of VO_2 because there is an excess of holes created by this type of doping. Therefore, it is obvious to consider the use of the nanoparticles of the vanadium dioxide doped p-type (15% Cr), as a suitable candidate for nano additives in fuels that can reduce the energy dissipated due to combustion and optimize energy efficiency. We strongly suggest the manufacturing of storage masses and optical memories based on the vanadium dioxide doped n-type (5%W), since we can exploit the increase in this dissipated energy as a function of temperature, as a means of increasing the storage speed of information.

Conflicts of interest
The authors declare that there are no conflicts of interest related to this article.

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