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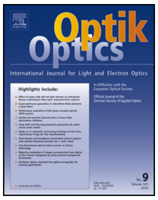

Quantity comprehension of optical hysteresis loop

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ABSTRACT

A theoretical model for quantity comprehension optical hysteresis loop is proposed, the model is derived from solution to decay rate differential equation together with boundary conditions. Because there are only four parameters in the model, it is easy to apply it. The model is verified by comparison with experimental data of vanadium oxides materials, the predicted results have an excellent consistency with experimental results. The maximum value of average relative error is 7.19% between measurements and theory, and the minimum data for the correlation coefficient in 18 fitted transmission-temperature curves is 0.994. Besides, it should be noteworthy that the calculation of hysteresis width is also very easy via parameters in this model. To the best knowledge of author, this is the first systemic theory to explain optical hysteresis loop.

1. Introduction

Vanadium oxides, such as VO, V_2O_3, VO_2, and V_2O_5, have been attracting a lot of interesting since this metal-insulator transition in metal-oxides [1]. Below one temperature, T, it's behaves like a semiconductor with a band-gap, while heating above another temperature transforms VO, V_2O_3, VO_2, and V_2O_5 in a metallic state. Hence, we define it as a metal-semiconductor transition, MST. The optical parameters can change drastically, affecting reflection and transmission [2,3]. Hysteresis is an especial characteristic that appears in ferroelectric, ferromagnetic materials, various smart materials, economics, and biology. Good fortune, hysteresis phenomenon appears in VO_2. The hysteresis phenomenon was observed at many wavelengths, such as at 1100 nm [4], at 2500 nm [5–7], at 700 nm [8], at terahertz [9], at 3000 nm [10], at 5000 nm [11], at 550 and 1500 nm [12]. Due to these unique property, VO_2 can be used as and smart windows, storage devices, switching devices and field effect transistors [4]. Nevertheless, different practical applications require different hysteresis width, for storage-type applications a larger hysteresis width is preferred, for switching-type applications, however, a smaller hysteresis width is needed. The base for knowing hysteresis width is hysteresis model. Phenomenological models are often constructed based on data without referring to physical properties, thus are widely adopted. Physics-based hysteresis models usually only work for a particular material, on the other hand, since they are often derived from specific physical properties. Prandtl–Ishlinskii (PI) model [13,14] and Preisach model [15–17] are among the most popular hysteresis models, and both have proven to be effective in hysteresis modeling and control for ferromagnetic materials. Although there have been these models, it is not easy to obtain hysteresis width.

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In this work, a hysteresis model is derived to capture sophisticated hysteresis of transmittance as observed in VO_2. After phenomenological considerations, a model with four parameters was derived from empirical principles. It can be argued that there was a simple empirical model fit to data and that it is with four parameters, however, only a little quantity information of application on this empirical function was provided [18]. Quantitatively estimating the hysteresis transmittance, T_r, via this characterization method agree with experimental data very well, it worth be noted that the hysteresis width can be easily determined through the best parameters in this model.

2. Simulation

The $T - T_r$ characteristics reflect the transient response of VO_2, so the hysteresis transmittance should be estimated via simple model. It is clearly observed that the transmittance decreases with increasing temperature during heating process, in other words, heating process is a decay process. Because the heating process is a Sigmoidal decay process, the model to explain T_r by T is Sigmoidal decay model [19]. According to the Sigmoidal decay rate, transmittance can be considered as solutions of the following differential equation and boundary conditions:

$$\begin{cases} \dfrac{dT_r}{dT} = \dfrac{n}{T}[1 - \dfrac{T_r(T) - \alpha_1}{\alpha_2}][\alpha_1 - T_r(T)] \\ T_r \Big|_{T\to 0} = T_{r_{\max}} \\ T_r \,|_{T\to\infty} = T_{r_{\min}} \end{cases} \tag{1}$$

where $T_{r_{\max}}$ is the maximum transmittance, $T_{r_{\min}}$ is the minimum transmittance, both α_1 and α_2 is related to $T_{r_{\max}}$ and $T_{r_{\min}}$. Integration of equations and boundary conditions in (1) gives

$$T_r(T) = T_{r_{\min}} + \frac{T_{r_{\max}} - T_{r_{\min}}}{1 + (T/T_0)^n}\, heating \tag{2}$$

where T_0 is central temperature, the average transmittance is fixed at T_0, n is power constant. It is not difficulty for one to write the model for cooling process,

$$T_r(T) = T`_{r_{\min}} + \frac{T`_{r_{\max}} - T`_{r_{\min}}}{1 + (T/T`_0)^{n`}}\, cooling \tag{3}$$

The coefficients $T_{r_{\max}}$ ($T`_{r_{\max}}$), $T_{r_{\min}}$ ($T`_{r_{\min}}$), T_0 ($T`_0$) and n (n‘) will be obtained by fitting the equation to the experimental results by the least-squares regression method. Where $\Delta T_0 = T_0 - T`_0$ denotes the width of the hysteresis. It is necessary to check whether models (2) and (3) can be used to calculate the actual hysteresis loops of optical transmittance when experimental hysteresis loops of optical transmittance are known. Hence, the model (2) and (3) are simulated on the experimental hysteresis loops of transmittance in nanostructured vanadium oxide films deposited on glass or glass/indium-tin oxide (ITO). Nanostructured vanadium oxide films deposited on glass substrates are libeled S1, S2 and S3 due to the deposition conditions of them are the same except for reactive O_2 gas flow rates [4], nanostructured vanadium oxide films deposited on glass/ITO substrates are libeled S4 and S5 because the deposition conditions of them are the same except for reactive O_2 gas flow rates [4], nanostructured vanadium oxide films deposited on glass substrates are libeled S6 and S7 due to the deposition conditions of them are the same except for annealing temperature, nanostructured vanadium oxide films deposited on glass substrates are libeled S8 and S9 due to the deposition conditions of them are the same except for annealing time [4]. Figs. 1 and 2 shows the hysteresis of transmittance at a fixed wavelength of 1100 nm as a function of temperature for S1–S9, Figs. 1 and 2 indicate that deposition conditions (reactive O_2 gas flow rates, annealing temperatures and annealing times) have important effects on the hysteresis of transmittance, especially the hysteresis width. The comparisons between theoretical and experimental hysteresis loops are also given in Figs. 1 and 2, the best functions to accurately link transmittance to temperature are listed in Table 1.

The average relative error, ARE, for T_r was calculated using the relation

$$ARE = \frac{1}{N}\sum_{j=1}^{j=N} \frac{\left|T_{r_{\exp}} - T_{r_{cal}}\right|}{T_{r_{\exp}}} \times 100\% \tag{4}$$

where $T_{r_{\exp}}$, $T_{r_{cal}}$ and N are values of the experimental and calculated T_r, the number of data points. The correlation coefficient, R, between the measurement and the theory data and average relative error are given in Table 1. Figs. 1, 2 and Table 1 confirm that model (2) and (3) do capture the hysteresis of optical transmittance. Therefore, the widths of the hysteresis for S1–S9 are figured out in Table 1, Table 1 states that S1, S4, S6, S8 and S9 are preferred for storage-type applications because their larger hysteresis width, and S2, S3, S5 and S7 are needed for switching-type applications due to their smaller hysteresis width.