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Resistance hysteresis loop characteristic analysis of VO_2 thin film for high sensitive microbolometer

Xiqu Chen*, Qiang Lv

School of Electrical & Electronic Engineering, Wuhan Polytechnic University, Wuhan, China

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ABSTRACT

Based on the Preisach model for hysteresis loop, the resistance hysteresis loop characteristic of thermosensitive VO_2 thin film is theoretically analyzed. The resistance characteristics dependent on temperature in the resistance hysteresis loop can be obtained through theoretical numerical calculation, and the numerical calculated results are in good agreement with the experimentally measured results of some VO_2 thin film samples in our laboratory. The resistance characteristics calculated results can be utilized to predict the infrared responsivity of high sensitive microbolometer of VO_2 thin film and direct the operating temperature optimization for microbolometer.

1. Introduction

Thin films of vanadium dioxide (VO_2) have been selected to fabricate microbolometer arrays mainly because of their excellent temperature coefficient of resistance (TCR) normally about −2% [1–3], and all current microbolometers for infrared detection based on VO_2 thin films work in the semiconductor state of these films at near room temperature. Although the present TCR of typical VO_2 thin film is adequate for a lot of infrared sensing applications, there are still strong demands for high-temperature-resolution infrared image system. Through nearly 20 years of research on VO_2 thin film fabricating technologies, it is legitimately speculated by some researchers that the TCR improvement of VO_2 thin film in semiconductor state is so difficult that that it may not be feasible. At the same time, selectable materials with high TCR values and other characteristics being suitable for microbolometric focal plane array are still nearly unavailable. Therefore, almost all of practical microbolometers are fabricated into a kind of micro-bridge structure for microbolometric focal plane arrays to improve their sensitivities [4–6]. However, the normal micro-bridge structure is limited to improve the response sensitivity of microbolometer and some complicated conceptual micro-bridge structure for microbolometer are nearly unchallengeable to be fabricated [7,8].

Because the TCR of VO_2 material in phase transition state can reach about −2 during a heating or cooling process [9], such a high TCR is very attractive to VO_2 microbolometer. But the phase transition temperature about 68 °C of conventional VO_2 material is too high to be utilized for infrared detection. With the development of fabricating process, some prototypes of VO_2 thin films have been successfully obtained with nanocrystalline structure. These nanostructured thin films can have low phase transition temperature values through the optimization of preparation process parameters [10,11]. Furthermore, the transition temperature of nanostructured VO_2 thin film can be further reduced by doping with metals such as tungsten and niobium or adjusting the thickness of the film [12,13]. Thus, the high TCR of nanostructured VO_2 thin film at normal temperature with a phase transition temperature approximate to room temperature becomes potential for infrared sensor applications.

Generally, the TCR of VO_2 thin film in phase transition state is only processed during a heating or cooling process and the TCR within the resistance phase transition hysteresis loop of nanostructured VO_2 thin film is scarcely tested and analyzed. When a microbolometer of VO_2 thin film works in phase transition state, it will be not only heated but also cooled. Then, it must be inaccurate to treat the TCR of VO_2 thin film within a hysteresis loop as the TCR during a straightforward heating or cooling process. To resolve this referring problem, we theoretically analyze resistance hysteresis loop characteristic of thermosensitive VO_2 thin film based on the Preisach model and point out how to obtain the resistance characteristics within the resistance hysteresis loop. The resistance characteristics can be used for predicting the infrared responsivity of future high sensitive microbolometer based on nanostructured VO_2 thin film.

2. Numerical calculation analysis

The Preisach model has been widely applied to describe electric or magnetic hysteresis loop, but it has seldom been adapted

* Corresponding author. Tel.: +86 13297969870.
E-mail address: cxqdhl@sina.cn (X. Chen).

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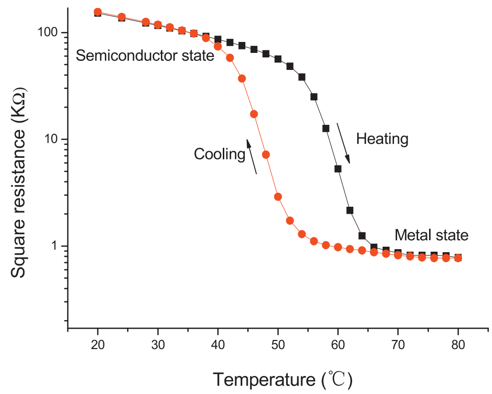

Fig. 1. Resistance thermal hysteresis loop of nanostructured VO_2 thin film.

for the thermal hysteresis loop analysis of VO_2 thin film [14,15]. Because normal VO_2 thin film is composed of tiny crystals and each crystal exhibits a very sharp hysteretic transition [16], the thermal hysteresis of the VO_2 thin film can be investigated with the adaptability of Preisach model. L. A. L. de Almeida adapted the Preisach model to describe the minor and major hysteresis loops in the resistance-temperature characteristics of VO_2 thin film, which operated in the high-temperature hysteretic transition region [17], but his description is almost impossible to be used for obtaining the microbolometer responsivity of VO_2 thin film. In order to get the resistance characteristics in the hysteretic transition region of VO_2 thin film for high sensitive microbolometer, we propose a kind of numerical calculation method based on the adaptation of the Preisach model in the following. The proposed method is theoretically simple and easy to be implemented with computer.

Based on the Preisach model, it can be gotten that a hysteresis loop can be treated as the synthesis of a sequence of different hysteresis units with different weighting factors. A typical resistance hysteresis loop of nanostructured VO_2 thin film in our laboratory is shown in Fig. 1 and its normalized mathematical model then can be illustrated in Fig. 2, in which each hysteresis unit $\gamma(\alpha, \beta)$ has a special weighting factor $\mu(\alpha, \beta)$. Thus, the normalized square resistance of the nanostructured VO_2 thin film at a certain temperature T can be expressed as

$$R(T) = R_{sat} + \iint_P \mu(\alpha, \beta)\gamma(\alpha, \beta)T d\alpha d\beta, \tag{1}$$

where R_{sat} is the normalized square resistance value of the nanostructured VO_2 thin film in metal state and the P is the domain of the pair of threshold temperatures α and β for every hysteresis unit.

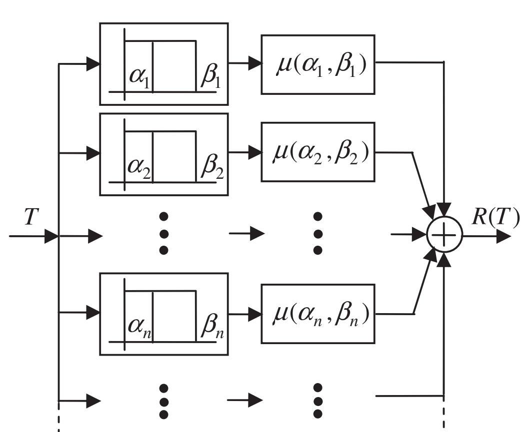

Fig. 2. The schematic of normalized Preisach mathematical model.

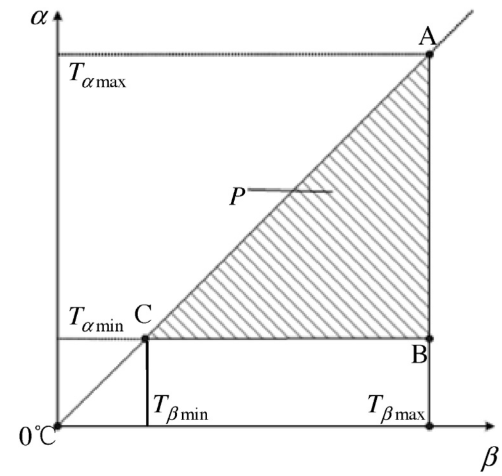

Fig. 3. The domain of temperatures α and β for hysteresis unit.

Considering that the heating branch threshold temperature β of each thermal hysteresis unit is greater than or equal to the cooling branch threshold temperature α and the pair of threshold temperatures α and β must have specific boundary values ($T_{\alpha\min} \le \alpha \le T_{\alpha\max}$ and $T_{\beta\min} \le \beta \le T_{\beta\max}$), we can get that the domain of the pair of threshold temperatures α and β for hysteresis unit is constrained within a certain triangle ABC, which is shown in Fig. 3 where $T_{\alpha\min} = T_{\beta\min}$ and $T_{\alpha\max} = T_{\beta\max}$. The triangle ABC is only associated with the resistance hysteretic characteristics portion in Fig. 1, lying between $T_{\alpha\min}$ and $T_{\alpha\max}$, and any one of weighting factor $\mu(\alpha, \beta)$ is zero outside of the triangle domain.

If the temperature of the VO_2 thin film is firstly cooled from T_0 ($T_0 < T_{\alpha\max}$) to T_1 and at last heated to T_2 as shown in Fig. 4, the corresponding domain of the pair of threshold temperatures α and β for hysteresis unit is illustrated in Fig. 5 and can be depicted as follows. The α and β firstly move from point D to point A along the line DC and then cover the triangle AEF, and at last wipe out the triangle FGH. Thus, the normalized square resistance of the VO_2 thin film at temperature T_2 is

$$R(T_2) = R_{sat} + \iint_{S_+} \mu(\alpha, \beta)\gamma(\alpha, \beta)T d\alpha d\beta, \tag{2}$$

where S_+ is the property of quadrangle AEGH. Because the product of $\gamma(\alpha, \beta)$ and T is equal to 1 within the domain of α and β, the square resistance expression of VO_2 thin film can be changed from Eq. (2) into

$$R(T_2) = R_{sat} + \iint_{S_+} \mu(\alpha, \beta) d\alpha d\beta. \tag{3}$$

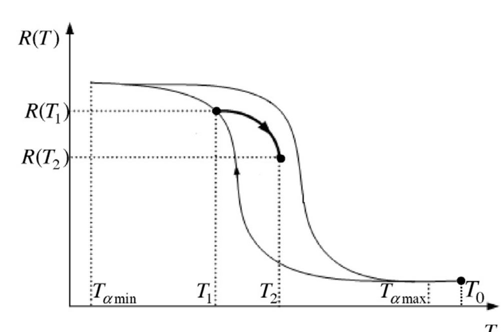

Fig. 4. The cooling and heating resistance curves of VO_2 thin film.