Low power-consumption analysis for optical switch based on VO_2 thin film

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The theoretical minimum driving power expression for the optical switch based on VO_2 thin film is given out in this paper, which is obtained from the phase transition characteristics and thermal structure of the VO_2 thin film, and it reveals some key parameters to decide its value. According to the theoretical expression, a kind of simple thermal structure fabricated with a low phase transition VO_2 thin film is proposed for low power-consumption optical switch. This kind of optical switch is compact and fast while requiring only a simple driving circuit, and the VO_2 thin film is deposited by using reactive ion beam sputtering method and formed by post-annealing process, which is compatible with IC process.

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1. Introduction

With the development of optical communication, low power-consumption optical switches are very important devices for high-speed and high-capacity optical networking in future [1,2]. Current micro-mechanical optical switches are compact and have excellent switching optical qualities, but their fabricating processes are complex and mechanical reliabilities are still challengeable [3]. Guide-wave switches have small sizes but poor optical properties such as high cross talk and high loss, and diode switches are fast but need special biasing circuits [4-6]. Optical switches for next generation optical networking should have excellent performance characteristics including small volume, high-speed, high-reliability, low power-consumption, and easy fabrication compatible with modern integrated circuit (IC) processes.

Vanadium dioxide (VO_2) thin films are good candidates for optical switching applications because of their sharp thermochromic phase transition characteristics [7-10], however, their normal phase transition temperatures about 68ºC are too high to be directly utilized for low power-consumption optical switches [11]. Although the phase transition temperatures of conventional VO_2 thin films fabricated by doping with tungsten or niobium can be lowered close to room temperature, the optical switching phase transition characteristics of these VO_2 thin films must be deteriorated [12]. In addition, the thickness adjustments of VO_2 thin films are often restricted for the decrease of phase transition temperatures [13].

Nanocrystalline VO_2 thin film is very attractive for its low phase transition temperature, based on which a kind of optical switch has been fabricated and its driving power dissipation and switching speed are preliminarily introduced in one of our published papers [14]. The ultimate minimum driving power-consumption for the optical switch based on the VO_2 thin film is theoretically analyzed and discussed in the following part, and a type of low power-consumption and high-speed optical switch fabricated with nanocrystalline VO_2 thin film is proposed in this paper.

2. Theoretical power-consumption analysis

The phase transition characteristics of a conventional VO_2 thin film is typically shown in Fig. 1, and the VO_2 thin film presents a pair of reversible states including a low-temperature semiconductor phase and a high-temperature metallic phase. The VO_2 thin film is optically transmissive in its semiconductor phase and reflective in the other phase [8], and its corresponding optical phase transition characteristics along the heating and cooling branches can be simplified as shown in Fig. 2, in which the heating phase transition temperature T_h is about 68°C greater than the cooling phase transition temperature T_l and the surroundings substrate temperature T_s of the thin film.

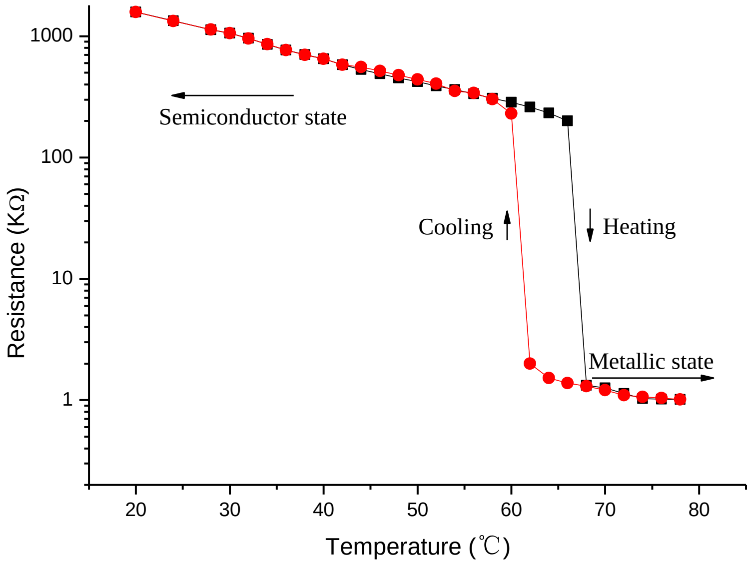

Fig. 1. Resistance phase transition characteristics dependent on temperature of the VO_2 thin film (color online)

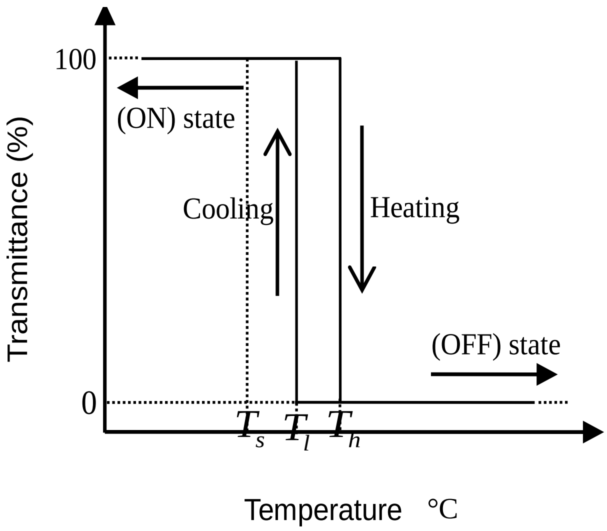

Fig. 2. Optical phase transition characteristics of the VO_2 thin film

If the VO_2 thin film is heated by a voltage source, it goes from the semiconductor phase into the metallic phase and turns from optical 'on' state to 'off' state correspondingly. Similarly, the VO_2 thin film is cooled from the metallic 'off' state into the semiconductor 'on' state when the voltage source is switched off. Assumed the driving voltage is U , the thermal balance equation of the VO_2 thin film is

$$c\frac{dT}{dt}=\frac{U^2}{R}-g(T-T_s), \tag{1}$$

where c is the heat capacity, R is the resistance, g is the thermal conductance of the VO_2 thin film. From equation (1), the temperature of the VO_2 thin film, which is time-dependent, can be gotten as

$$T(t)=T_s+\frac{U^2}{Rg}(1-e^{-t/\frac{c}{g}}). \tag{2}$$

After about 5 times time constant c/g , the temperature of the VO_2 thin film enters a steady state and is

$$T=T_s+\frac{U^2}{Rg}. \tag{3}$$

To ensure the optical switching function of the VO_2 thin film, the heating steady temperature of the VO_2 thin film must be

$$T\geq T_h, \tag{4}$$

And that is

$$U \geq [(T_h - T_s)Rg]^{\frac{1}{2}}. \tag{5}$$

The driving switching response of the VO_2 thin film is illustrated in Fig. 3, in which the driving voltage is

$$U = [(T_h - T_s)Rg]^{\frac{1}{2}}, \tag{6}$$

and that is the ultimate minimum driving power-consumption is

$$P_m = (T_h - T_s)g \tag{7}$$

At the same time, the maximum switch driving frequency of the VO_2 thin film can be obtained from Fig. 3 as

$$f_{\max} \approx \frac{1}{2 \times \frac{5c}{g}} = \frac{g}{10c} \tag{8}$$

From equation (8), it can be found that the small heat capacity c and the large thermal conductance g can lead to the high-speed optical switch based on the VO_2 thin film. However, the heat capacity c cannot be lowered without limits, which is dependent on the thickness and area of the VO_2 thin film, and the larger thermal conductance g must result in the larger minimum driving power-consumption. Thus, it can be said that the small heat capacity c, the appropriate thermal conductance g, and the low heating phase transition temperature T_h can produce the low power-consumption optical switch with a high-speed switching function.

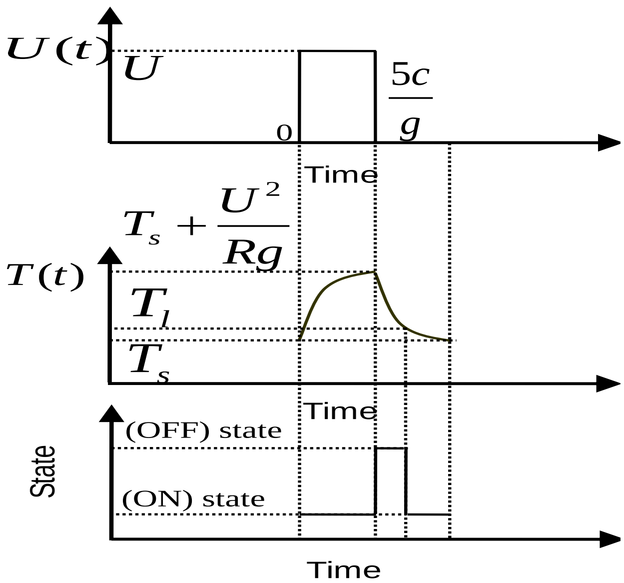

Fig. 3. Driving switching response of the VO_2 thin film

3. Proposed optical switch structure

In order to fabricate a low power-consumption optical switch while maintaining its high switching speed, a kind of simple thermal structure for the optical switch is proposed in Fig. 4. The VO_2 thin film is supported by a thermally isolated Si_3N_4 buffer layer and can be connected to a driving voltage source through the pair of NiCr electrodes. The switching function of the optical switch is realized through the optical phase transition characteristics of the VO_2 thin film. This kind of optical switch is compact for all-optical networking.

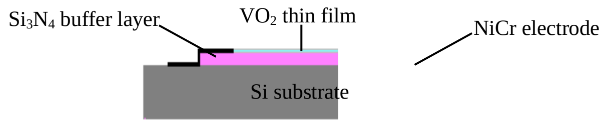

Fig. 4. Thermal structure for the proposed optical switch

The fabricating procedure for the optical switch mainly contains three processes, which is illustrated in Fig. 5. At first, the thermally isolated Si_3N_4 buffer layer is deposited and etched to form a sandwich structure, which plays roles of supporting and insulating for the VO_2 thin film. Secondly, the VO_2 thin film is fabricated and patterned by wet etched method. The size and thickness of the VO_2 thin film are determining factors for its heat capacity, and it can be said that the smaller size and thinner thickness mean the smaller heat capacity. The optical phase transition performance and fabricating steps of the VO_2 thin film will be introduced in the following two paragraphs. At last, the metal NiCr conductive layer is deposited and electrode shape is formed by lift-off method.

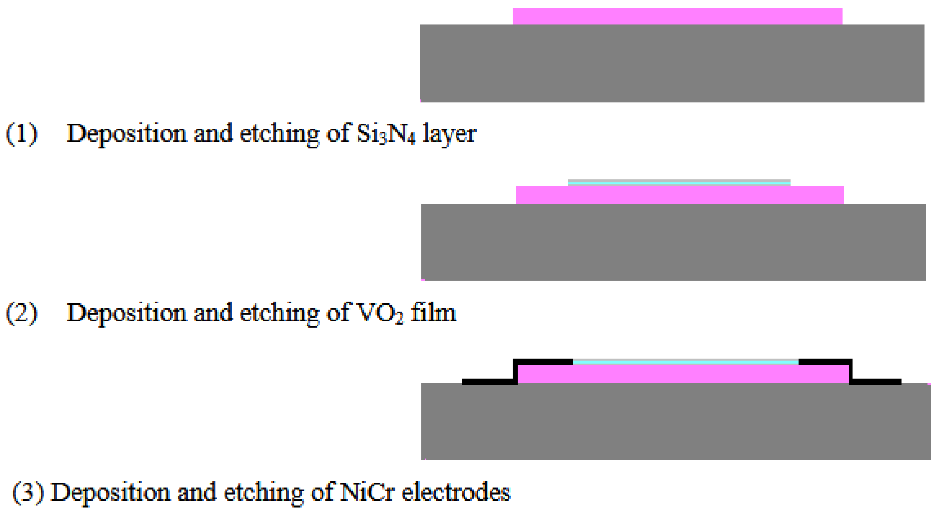

Fig. 5. Fabricating procedure for the optical switch (color online)

In the simple structure for the optical switch, the optical phase transition performance of the VO_2 thin film is vital. The VO_2 thin film fabricated in our laboratory has excellent low temperature phase transition optical properties and its heating phase transition temperature can be lowered to be about 50℃, which is shown in Fig. 6. At the same time, the cooling phase transition temperature of the VO_2 thin film is about 40℃, which is above the normal surroundings substrate temperature and can make the VO_2 thin film enter its ‘on’ state after the driving voltage source is turned off. In order to make sure that the VO_2 thin film can go into its optical ‘on’ state from ‘off’ state, the cooling phase transition temperature of the VO_2 thin film must be above the surroundings substrate temperature T_s decided by the ambient temperature, driving power, and heat-sinking capability of the optical switch.

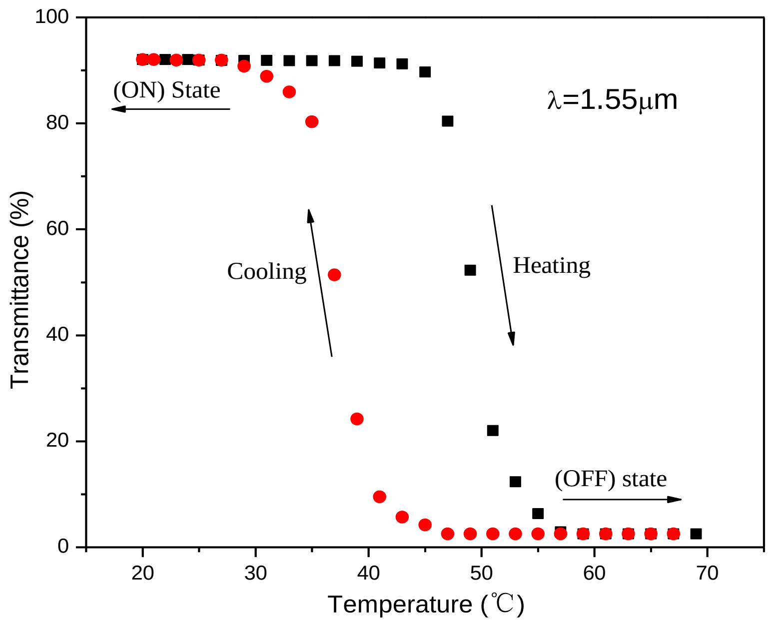

Fig. 6. Optical switch properties of the VO_2 thin film (color online)

The VO_2 thin film has been fabricated in our laboratory through two steps: the first is ion beam sputtering and the second is annealing, and these two steps are completely compatible with integrated circuit (IC) process.

The X-ray diffraction (XRD) measurement results of the experimentally fabricated VO_2 thin film on Si substrate are shown in Fig. 7, and it clearly indicates that the thin film consists of only pure VO_2. The further test of atomic force microscope (AFM) on the VO_2 thin film exhibits that the thin film has nanocrystalline structure, which is shown in Fig. 8.

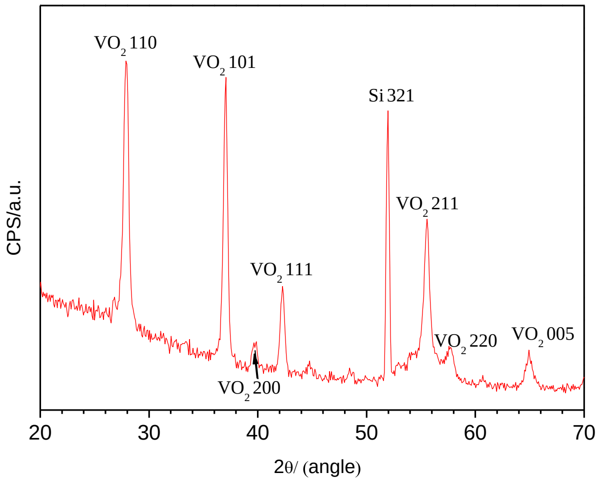

Fig. 7. XRD measurement results of the fabricated thin film (color online)

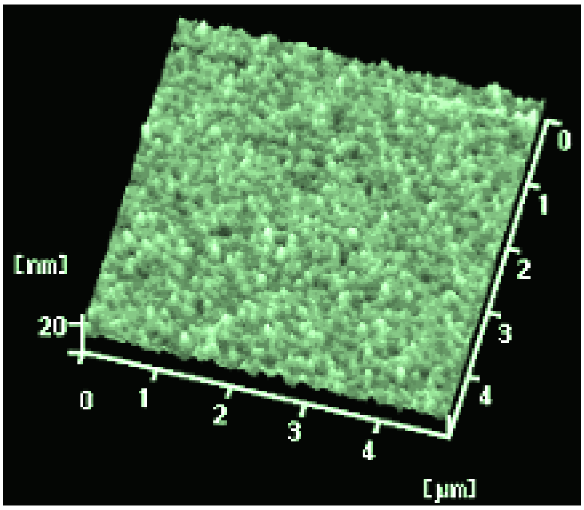

Fig. 8. AFM tested photograph of the fabricated thin film (color online)

An experimental prototype of 2×10 micro-optical-switch matrix is fabricated in our laboratory, and its part SEM photograph of 2×3 micro-optical-switches is shown in Fig. 9. The heat capacity c and the thermal conductance g of one typical micro-optical-switch are separately controllable to be 1×10^{-9}W/K and 1×10^{-3}J/K, and the relationship between the transmittance and driving power of the typical micro-optical-switch with the surroundings substrate temperature about 30°C in the matrix is investigated and shown in Fig. 10. The minimum driving power of the micro-optical-switch is about 20mW and its maximum switch frequency can reach about 0.1MHz, which is consistent with the previous theoretical analysis. It is worthwhile noting that the minimum driving power of the micro-optical-switch can be further lowered while maintaining or increasing its switch speed through the optimization of the heat capacity and the thermal conductance.

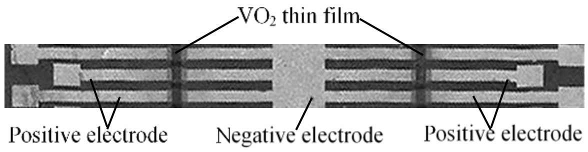

Fig. 9. SEM part photograph of 2×10 micro-optical-switch matrix

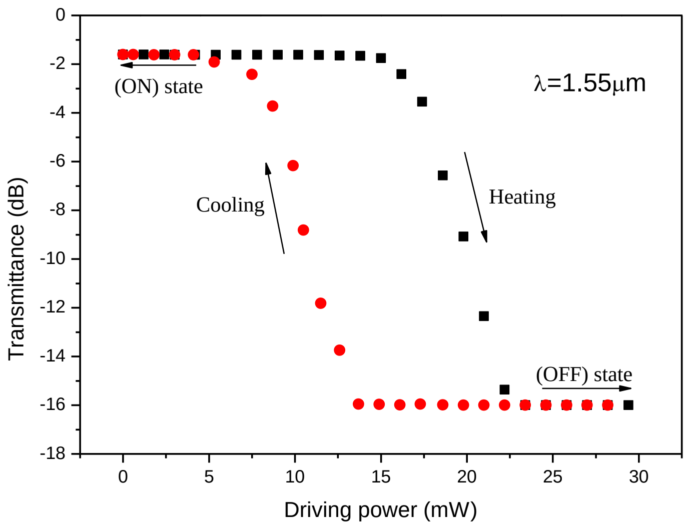

Fig. 10. Relationship between transmittance and driving power of one typical micro-optical-switch (color online)

4. Conclusions

The driving power of optical switch based on VO_2 thin film is theoretically discussed, according to which a kind of simple structure optical switch is proposed. For low power-consumption optical switches, the phase transition characteristics and thermal structure parameters of VO_2 thin film are vital. The phase transition temperature of the VO_2 thin film fabricated in our laboratory can be lowered to be about 50 ℃, and those two thermal structure parameters and of the proposed optical switch are independently controllable. Measured and tested results indicate that the micro-optical-switch fabricated in our laboratory has excellent characteristics including low power-consumption about 20mW and switch frequency about 0.1MHz.

Acknowledgments

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References

[1] B. G. Lee, Optical Fiber Communication Conference, 1 (2018).
[2] C. P. Singh, K. S. Bindra, B. Jain, S. M. Oak, Optics Communications **245**(1-6), 407 (2005).
[3] L. Y. Lin, E. L. Goldstein, R. W. Tkach, IEEE Journal of Selected Topics in Quantum Electronics **5**(1), 4 (1998).
[4] G. F. R. Chen, J. R. Ong, T. Y. L. An, S. T. Lim, C. E. Png, D. T. H. Tan, Scientific Reports **7**, 1 (2017).
[5] C. C. Chiang, C. W. Tsai, Optics Communications **278** (1), 42 (2007).
[6] A. V. Bolotnikov, P. G. Muzykov, IEEE Transactions on Electron Devices **54**(6), 1540 (2007).
[7] C. F. Case, Journal of Vacuum Science & Technology A Vacuum Surfaces & Films **8**(3), 1395 (1990).
[8] R. O. Dillon, K. L. N. Ianno, Thin Solid Films **398**, 10 (2001).
[9] S. Chen, M. Hong, X. Yi, H. Wang, T. Xiong, M. Chen, X. Li, C. Ke, Infrared Physics & Technology **45**(4), 239 (2004).
[10] J. Y. Suha, E. U. Donev, R. Lopez, L. C. Feldman, R. F. Haglundet, Applied Physics Letters **88**(13), 667 (2006).
[11] L. A. Gea, L. A. Boatner, Applied Physics Letters **68**(22), 3081 (1996).
[12] M. Soltani, M. Chaker, E. Haddad, R. V. Kruzelecky, D. Nikanpour, Journal of Vacuum Science & Technology A Vacuum Surfaces and Films **22**(3), 859 (2004).
[13] Y. Muraoka, Z. Hiroi, Physics Letters **80**(4), 583 (2002).
[14] X. Chen, Q. Lv, Optik **124**(7), 579 (2013).

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