EPJ Web of Conferences **266**, 05011 (2022)
EOSAM 2022
https://doi.org/10.1051/epjconf/202226605011

Switchable optics based on guided mode resonance in lithographically patterned vanadium dioxide

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Abstract. Vanadium dioxide as a phase change material is usually known for its consideration in smart window applications. However, the attention shifts to using it in actively switched optical elements. The main challenges are the deposition of vanadium dioxide with the correct stoichiometry and phase and the patterning of the material. We propose a design with a corresponding manufacturing process for an actively switchable reflector at 1550 nm wavelength with a contrast near 10^5 by using the thermochromic effect of vanadium dioxide. The reflectance of the proposed optical element can be controlled between an ultra-low and a high reflecting state. We elaborate on the proposed optical design, the manufacturing process including deposition, annealing and patterning processes, and discuss already achieved results.

1 Introduction

The reversible semiconductor to metal transition (SMT) of vanadium dioxide (VO_2) at a critical temperature of T_{crit} = 68 °C was first found in 1959 [1], since then many potential applications were described. Including, but not limited to, smart windows [2], adaptive optics [3], and optical switches [4]. The SMT is accompanied by a structural phase transition from the low-temperature monoclinic VO_2(M) to the high-temperature rutile VO_2(R) crystal structure [5], and several changes in physical properties, like the change in electrical resistivity, refractive index, and extinction coefficient, among others.

The hereby proposed design for an actively switching reflector with high switching contrast is based on guided mode resonances. We use a one-dimensional grating with a period of 1 µm on a stack of conductive and nonconductive films (fig. 1). The underlying layer stack serves as a resistive heating element to achieve the phase transition of vanadium dioxide. The heating element consists of a thin film of indium tin oxide (ITO) covered with chromium contacts for the connection of a regulated power supply. On top of the heating element is an electrically non-conductive film of silicon oxide. It isolates the heating element from the vanadium dioxide (VO_2) grating.

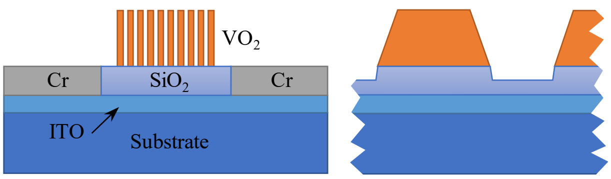

Fig. 1. Design of the resistive heating element underneath and waveguide structure on top. Both parts are electrically isolated by a thin film of SiO_2. The dimensions are not to scale.

The aim of the optical design of the grating is to switch the reflection at the wavelength of λ = 1550 nm. At room temperature (and below T_{crit} = 68 °C), incoming light is coupled into the waveguide structure and absorbed. With rigorous coupled wave analysis (RCWA), the reflectance of this structure can be calculated to be below $R < 0.001\%$. If the temperature rises above T_{crit}, the material changes to the metallic phase and the waveguide grating becomes reflective ($R > 45\%$). This leads to a switching contrast near to 10^5.

2 Manufacturing

A single side polished silicon wafer with <100> orientation is used as a Substrate. ITO was deposited using a sputtering process. The chromium and silicon oxide films were deposited by ion beam deposition and reactive ion beam deposition (IBD/RIBD), respectively. Both layers were patterned by a lift-off process utilizing AZ®nLOF 2070 from MicroChemicals. Afterwards, a vanadium dioxide film was deposited with RIBD. Using X-ray photoelectron spectroscopy (XPS) and Auger electron spectroscopy (AES), we were able to determine the stoichiometric composition and ratio of vanadium to oxygen in the resulting film depending on the oxygen partial pressure during the deposition. The partial pressure of oxygen was controlled by variation of oxygen flow rate. After deposition, an annealing of the layer at 520 °C for 30 min in an atmosphere composed of nitrogen and oxygen in a 100:1 ratio and a pressure of 10 mbar was necessary to form VO_2(M). The formation of this phase could be validated by Raman spectroscopy. We developed a recipe for reproducibly manufacturing VO_2 layers of different thicknesses ranging from at least 100 nm to 300 nm. The resulting layer was patterned by a lift-off process prior to the annealing.

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The VO_2 layer was patterned by inductively coupled plasma (ICP) etching against a chromium hard mask. The latter was patterned using e-beam lithography with positive tone resist FEP-171 (Fujifilm) and reactive ion etching (RIE) directly on the VO_2. After etching the VO_2, the chromium was removed from the top of the ridges with RIE. The presence of the phase change material VO_2(M) in the patterned layer was verified by using Raman spectroscopy.

3 Results

3.1 Complex refractive index of VO_2

The refractive index n (fig. 2 a)) and extinction coefficient k (fig. 2 b)) were measured on samples of VO_2 thin film deposited using RIBD on a silicon substrate by variable angle spectroscopic ellipsometry (VASE). The samples were measured at 25 °C and 90 °C. The temperature was controlled by a regulated hot plate to the specified temperature.

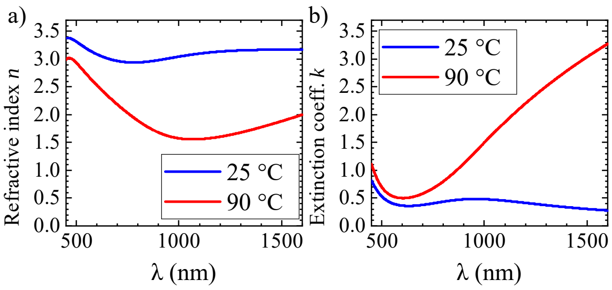

Fig. 2. a) refractive index n and b) extinction coefficient k of prepared VO_2 film below and above the SMT.

3.2 Raman spectra

The Raman spectra (see fig. 3) measured before and after the annealing process show the reconfiguration of the thin film to form crystalline phase of VO_2(M). Most prominent are the two sharp peaks of VO_2 at 194 cm^{-1} and 224 cm^{-1} and the broader peak at 612 cm^{-1}. The peak at 520 cm^{-1} is due to the Si substrate material. The insets show an SEM image of an edge of the respective films on Si substrate.

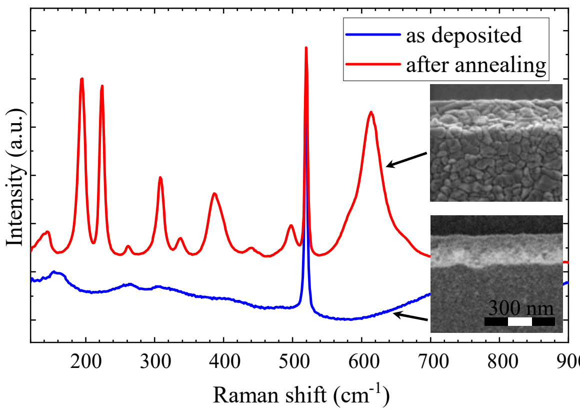

Fig. 3. Raman spectra of VO_2 film on Si: as deposited and after annealing. The insets show SEM images of the respective films.

3.3 Transmission

As an optical performance test, the transmission was measured at $\lambda = 1550$ nm on a non-patterned VO_2 layer with thickness of 265 nm (fig. 4). The sample was heated by applying a heating current to the resistive heating element directly in contact to the VO_2 thin film. Depending on the temperature, the transmission could be switched between $T = 43.6\%$ and $T = 0.17\%$. contrast of $c_T > 250$. According to RCWA, the maximum switching contrast in transmission for the film thickness is $c_T = 375$.

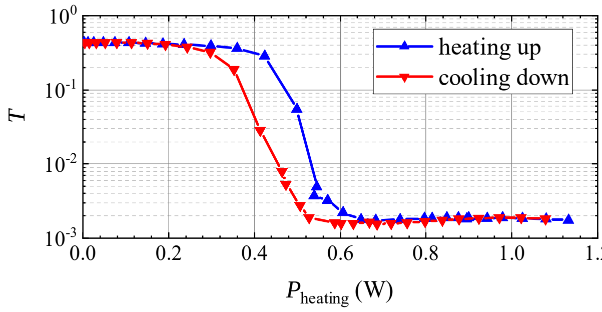

Fig. 4. Transmission change of optical element in relation to heating power inserted in resistive heating film. Each measurement was taken after thermal equilibrium was reached.

4 Conclusion

We presented a design for an actively switching reflector with high switching contrast based on guided mode resonances. Furthermore, we established a manufacturing process for e-beam lithography on VO_2 thin films deposited by RIBD. Characteristic Raman peaks were observed for thin films and patterned layers. These results are very promising for the optical function of such an optical switch. Next, we plan the optical characterisation of the reflector.

Acknowledgement

The authors acknowledge the financial support by the Federal Ministry of Education and Research (BMBF) of Germany and VDI (funding no. 13N15175). This work is funded through the project 20IND04 ATMOC within the Programme EMPIR. The EMPIR initiative is co-founded by the European Unions Horizon 2020 research and innovation program and the EMPIR Participating Countries.

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