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Optimizing VO_2 film properties for use in SAW devices

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The aim of this study is to optimize the conditions for producing thin VO_2 films for their use in SAW devices. We used the pulsed laser deposition (PLD) method to produce VO_2 films. We used a metallic vanadium target. The dependence of the oxygen pressure during PLD on the resistive metal–insulator transition (MIT) on substrates of *c*-sapphire and $LiNbO_3$ YX/128° was studied. The resulting films had sharp metal–insulator temperature transitions on *c*-Al_2O_3. The most high-quality films showed resistance change by four orders of magnitude. At the lower point of the hysteresis, the resistance of these samples was in the range of 50–100 Ω. The synthesized VO_2 films had a sharp temperature transition and a relatively small width of thermal hysteresis. The SAW damping during its passage through a VO_2/ZnO/$LiNbO_3$ YX/128° film at the metal–insulator phase transition temperature was studied. Attenuation SAW decreases with increasing temperature from 52 dB/cm to 0 dB/cm.

Keywords: Surface acoustic wave; VO_2 film; laser pulsed deposition; parameter S_{21}; metal–insulator transition.

1. Introduction

Vanadium dioxide (VO_2) exhibits a metal–insulator transition (MIT) at a temperature of about 69 °C.[1,2] In this transition, the resistivity of VO_2 changes up to four orders of magnitude.[3] The existence of the temperature, light, electrically or mechanically metal–insulator switch in vanadium dioxide (VO_2) at near-room temperature (~68 °C),[4] combined with a short time of switching from the dielectric state to the metallic state (~26 fs),[5] a sharp change in resistance (more than four orders of magnitude),[6] a narrow width of the transition (about $\Delta T_c \sim 1°$ in the best epitaxial films),[7] the ability to change the capacity of thin-film structures with an electric voltage[8] allows VO_2 to be considered as a promising material for use in controlled devices based on surface acoustic waves (SAW), broadband SAW photodetectors (from UV to IR range), controlled by light and electrically SAW couplers, switches and reflectors. Various methods such as magnetron sputtering[11,12] sol–gel method,[13] chemical vapor deposition,[14,15] molecular beam epitaxy (MBE)[16,17] and pulsed laser deposition (PLD)[7,18,19] are used to make VO_2 thin films. Among all these methods, PLD is one of the most successful methods.

VO_2 films fabricated by PLD at different O_2 pressures on Al_2O_3 (0001) substrates were studied in Ref. 18. All films exhibited thermal hysteresis behavior. The greatest change in resistance (~5 × 10^3 times) was demonstrated by a film obtained at an oxygen pressure of 2.7 Pa. The film resistance varies from 7 × 10^4 to 150 Ohm.

Similar studies were carried out by the authors of Ref. 19, using (1010) Al_2O_3 M-cut substrates, different deposition temperatures and different cooling times of the substrates after deposition. The smallest resistance was observed for samples that were synthesized at 630 °C and cooled for 1 and 3 h. The resistance of the samples varied from 2 × 10^5 to 4.1 Ohm.

Quite similar results were obtained in Ref. 20 for VO_2 films fabricated by PLD, also at 630 °C on Al_2O_3 C (0001) and M (1010) cuts. The resistances of the samples varied approximately 10^5 times from 4 × 10^5 to 4 Ohm.

2. Synthesis of VO_2 Films

To create VO_2 films on a *c*-Al_2O_3 substrate, we used the method of laser pulsed deposition. A metal V target was placed at a distance of 5 cm from the substrate. Radiation from a KrF (248 nm, 10 Hz) laser was focused on the surface of a rotating target with a power density of 2.3 J/cm². The substrate temperature was maintained at (550–650 °C), and the oxygen atmosphere in the vacuum chamber was (3–6) × 10^{-2} mbar.

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After the deposition of the films, the samples were kept in an O_2 atmosphere at 650 °C for 20 min, and then they were also cooled in an O_2 atmosphere.

The VO_2 layer was deposited by the PLD method from a metallic vanadium target using the above-described technique of *in situ* annealing of the preliminary layer. The first thin layer of VO_2 was deposited in 700 laser pulses with a laser pulse repetition rate of 5 Hz. The substrate temperature was 620 °C, and the O_2 partial pressure was 5×10^{-2} mbar. Then, *in situ* annealing was performed for 5 min. P (O_2) was 5×10^{-2} mbar, substrate temperature was 620 °C. Then, *in situ* annealing was performed for 5 min. P (O_2) was 5×10^{-2} mbar, the substrate temperature was 620 °C. Then the main VO_2 layer was deposited (laser pulse repetition rate 10 Hz, substrate temperature 620 °C, oxygen pressure 5×10^{-2} mbar). After the deposition of the main layer, one more *in situ* annealing was carried out without changing the O_2 pressure and temperature for 10 min. Then the sample was cooled to a temperature of ~150 °C in an oxygen atmosphere of 5×10^{-2} mbar.

3. Results and Discussion

3.1. *Structural properties of VO_2 films*

The X-ray diffraction (XRD) measurements were carried out using an ARL XTRA diffractometer with CuKα-radiation at 35 kV and 30 mA. The scan step was 0.02°. The XRD pattern of a typical VO_2 film deposited on *c*-Al_2O_3 substrate shown in Fig. 1 reveals peaks at 39.9° and 86° which correspond to (020) and (040) reflexes of monoclinic VO_2 phase. No other peaks were observed which claims that the films are epitaxial with (010) planes oriented parallel to *c*-Al_2O_3 substrate. FWHM of (002) and (040) peaks were measured to be as narrow as 0.18° and 0.20°, correspondingly, which claims on a high crystalline quality of prepared films. The unit cell parameter *c* calculated from the positions of (020) and (040) reflexes is 0.4521 nm which is slightly different from *c* = 0.4532 nm for monoclinic VO_2 powder sample, exhibiting minor compressive stresses due to film and substrate lattice parameters mismatch.

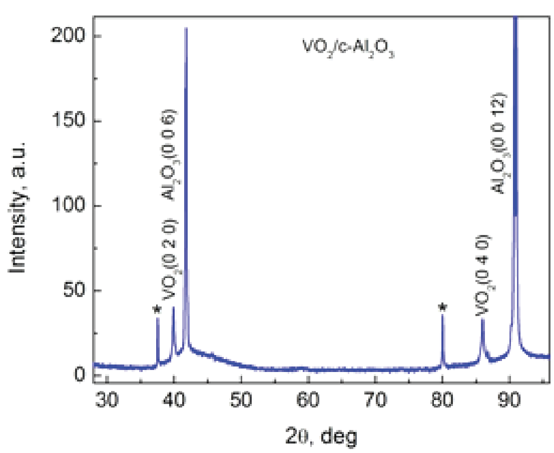

Fig. 1. XRD pattern of VO_2 film on *c*-Al_2O_3 substrate deposited at 650 °C and oxygen pressure of $6 \cdot 10^{-2}$ mbar; *denote parasite peaks of a sapphire substrate.

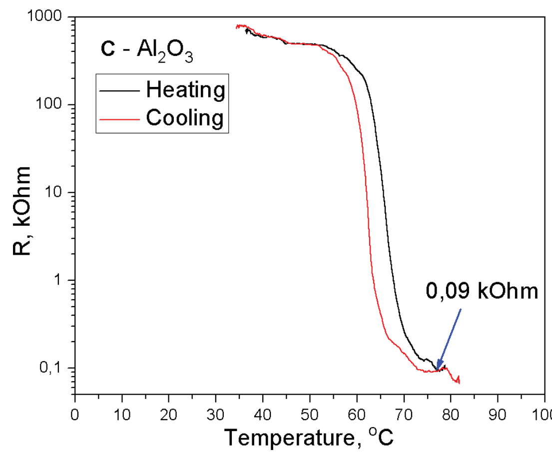

Fig. 2. Dependency of resistivity from temperature in VO_2 films on *c*-Al_2O_3.

3.2. *Study of temperature induced resistance alteration in VO_2 films*

The most high-quality VO_2 films on *c*-Al_2O_3 showed a change in resistance by four orders of magnitude. At the lower hysteresis point the resistance of these samples was in the range (40–100) Ohms (Fig. 2). It should be noted that our films exhibit a rather sharp transition and a relatively small hysteresis width, which indicates the high quality of the obtained material.

For VO_2 films on a $LiNbO_3$ YX/128° piezoelectric substrate with a buffer ZnO sublayer, the temperature dependence of the resistance is shown in Fig. 3.

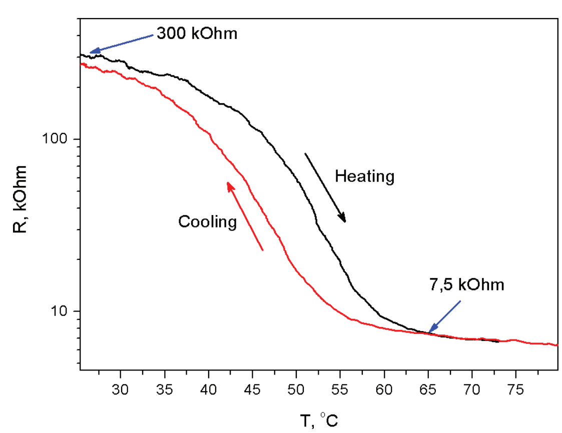

Fig. 3. Dependency of resistivity from temperature in VO_2 on $LiNbO_3$ YX/128° substrate with ZnO buffer layer.

At room temperature, the resistance of the VO_2 film was ~300 kOhm, and at a temperature of 65 °C, it was 7.5 kOhm.

4. SAW Measurements

To study the attenuation of a surface acoustic wave (SAW) when passing through a thin VO_2 film in the temperature range of the metal-semiconductor phase transition, a special stand was made, the design of which is shown in Fig. 4. It contains two YX/128° cut lithium niobate substrates, each of which has a unidirectional IDT with internal reflectors[9] at a central frequency of 120.7 MHz. The ends of the substrates are rounded so that a SAW absorber can be applied to them. IDTs contain 17 unidirectional sections with an aperture of 1.2 mm. The substrate, which is placed on top, provides the transition of the SAW from one position with one IDT to another substrate with another IDT. This is due to the fact that SAWs are accompanied by an electric field and excite a SAW in the upper piezoelectric substrate. A vanadium dioxide film is deposited on the surface of the upper substrate. The absence of IDTs on this substrate significantly expands the possible parameters of the synthesis of the vanadium oxide film and makes it possible to study the vanadium oxide film immediately after its deposition. Next, the SAWs by their electric field excite the SAWs in another substrate, on which one more IDT is located. Piezoelectric substrate without IDT, but with a film of vanadium oxide is pressed against piezoelectric substrates with IDT using a clamping screw, through a heater. S-parameters were recorded by using a network analyzer OBZOR 304/1. The electromagnetic signal is converted into a SAW using an IDT, then the SAWs propagate to another IDT, passing first to a piezoelectric substrate with a vanadium oxide film, and then to another substrate with an IDT. In this case, the distance traveled by the SAW is 58 mm, which corresponds to a delay of 14.28 μs.

Figure 5 shows the change in the amplitude–frequency characteristic of SAW S_{21} when the sample is heated from 30 to 60 °C. It can be seen that at a temperature of 30 °C, the SAW attenuation is 17 dB greater than at 60 °C. This is due to the fact that at a temperature of 30 °C the resistance of the film is about 300 kΩ, while the film is in a semiconducting state. At the same time, at 60 °C, the film resistance is less than 10 kOhm and it is in a state close to metallic. Therefore, the SAW, passing under the film at 30 °C, experiences acoustoelectronic interaction[20,21] with charge carriers in the film, which leads to a significant acoustoelectronic SAW. When the film is in a state close to metallic, it screens the electric field of the SAW and the acoustoelectronic interaction is small. In this case, acoustoelectronic damping is also small. Figure 6 shows the dependence of the SAW decay at temperatures near the metal-semiconductor VO_2 phase transition. Such dependence was constructed from the frequency dependences of the parameter S_{21}, taken at different temperatures, both in the direction of increasing the temperature and in the direction of decreasing it. In this case, the SAW attenuation was measured by the maximum amplitude–frequency characteristic of the parameter S_{21} at a frequency of 120.7 MHz, taking into account the length of the VO_2 film equal to 3 mm.

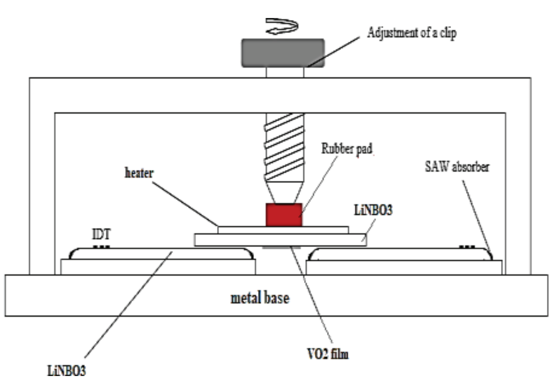

Fig. 4. Experimental setup for measuring the attenuation of a surfactant in a vanadium oxide film.

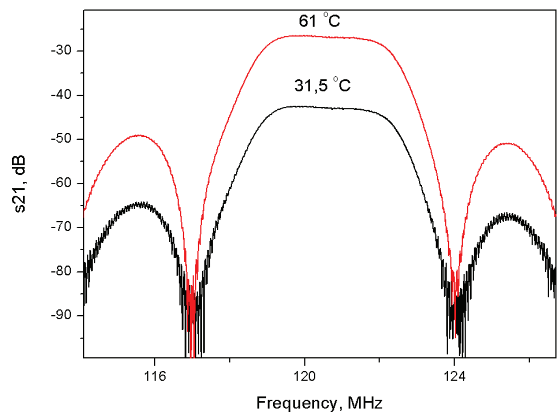

Fig. 5. Change in the amplitude–frequency characteristic of SAW S_{21} when the sample is heated from 31.5 °C to 60 °C.

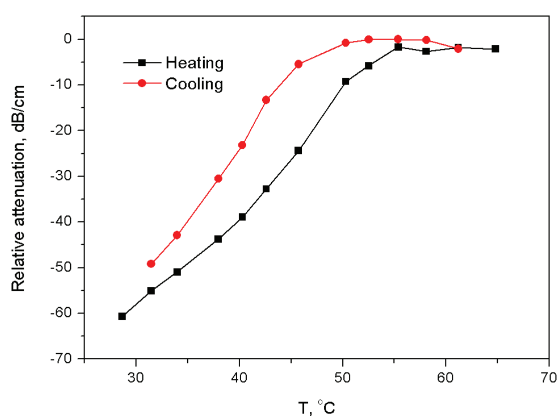

Fig. 6. Changes in the attenuation of a SAW when passing through a thin VO_2 film in the temperature range of the metal-semiconductor phase transition.

5. Conclusions

An investigation was made of vanadium dioxide films obtained by PLD from a metal target. A narrow semiconductor-metal junction, a large change in resistance (change by four orders of magnitude) and a low resistance value at the end of the junction (90 Ohm) determine the prospects for using VO_2 films on c-Al_2O_3 in impedance-dependent SAW devices.[10] A significant change in SAW attenuation (~19 dB) in VO_2 films on piezoelectric substrates at semiconductor-metal phase transition temperatures determines the prospects for using VO_2 in temperature-controlled or light-controlled SAW devices.

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