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Fast optical activation of insulator-to-metal transition in vanadium dioxide (VO₂) phase changed materials

Aurelian Crunteanu*, Jean-Christophe Orlianges, Annie Bessauadou
XLIM Research Institute, CNRS/University of Limoges, 123 avenue Albert Thomas, 87060
Limoges, France

ABSTRACT

Vanadium dioxide (VO₂) is undergoing a reversible insulator-to-metal transition (MIT), subject to thermal, electrical or optical stimuli. The transition is accompanied by drastic changes in the material's electrical and optical properties which, along the MIT broadband frequency response (from DC to microwaves, THz/ optical domains), triggered a plethora of interesting applications (DC to millimeter-waves switching, THz modulators, reconfigurable filters and antennas etc.). Here we report on optical switching of the VO₂ material between its two dissimilar states when integrated in planar two-terminal electrical devices and submitted to laser pulses with different temporal lengths from a high-power laser diode operating at 980 nm. During optical irradiation of VO₂ films with pulses having mean powers between 15mW and 140mW at repetition rates up to 500 kHz, we monitored its resistance change, witnessing on the MIT onset. We demonstrate that the MIT in VO₂ is optically triggered for pulses as short as 25 ns and energies higher than 130 nJ/pulse, with insulator-to-metal response times in the range 10-15 ns. The process is highly stable and reliable; the devices are able to perform more than one billion switching cycles at frequencies up to 400 kHz without damaging the material nor the device integrity. This optical activation scheme of VO₂ emerges as a promising solution for reconfiguration applications at THz and millimeter-waves frequencies.

Keywords: vanadium dioxide, metal-insulator transition, optical activation, electrical high-frequency switches

1. INTRODUCTION

Recent advances in telecommunication systems for civil, defense or space applications, calls for adaptive reconfigurable circuit components at microwave and millimeter-wave frequencies. In order to address the problems related to the increasing number of telecommunication standard multiplication, increasing operating frequencies and overlapping of operating bands, a lot of research have been conducted towards tunable and switchable approaches. Development of smart multifunctional materials with novel properties can be a viable solution for realizing electronic devices with small footprint and faster response time. Strongly correlated oxide materials exhibiting metal-insulator transition (MIT) have been considered as candidates for a large number of applications, including RF switches^{1,2}, reconfigurable antennas^{3,4}, and filters^{5,6}, due to the large contrast in conductivity between the two states along their phase transition. Among them, vanadium dioxide (VO₂) displays near room temperature phase transition, with an insulating state in the room temperature and a metallic state for temperatures higher than 68°C^{7,8}. The electrical resistivity of VO₂ changes by 3–5 orders of magnitude between insulating and metal states, which makes it a promising candidate for switching devices, offering easier integration in microelectronic technological processes, faster response time and smaller footprint^{7,8}. Insulator to metal transition in VO₂ can be triggered by different external stimuli: temperature, optical, electrical-charge injection, and pressure⁷⁻¹¹. Recent studies showed that electrically- induced MIT in VO₂ can have switching times down to several nanoseconds^{9,10}. VO₂ integration in RF/ microwave devices has been already demonstrated as active, tunable elements using their thermal and electrical activation for phase shifters, filters or power limiters^{1-6, 12-14} on broad frequency bands and power handling higher than 30 dBm, less is reported on the practical integration of an optical activation scheme of MIT in VO₂-based RF switches.

In this paper, we report on the electrical properties and optical activation of planar RF switches integrating VO₂ two-terminal devices in single-pole single-throw (SPST) coplanar waveguide (CPW) topology. We are demonstrating that the optical activation scheme of VO₂ material may be a fast, reliable switching solution for RF functions showing performances better than the current semi-conductor approaches.

*aurelian.crunteanu@xlim.fr; phone +33 (0) 5 87 50 67 41; fax +33 (0) 5 55 45 76 49; www.xlim.fr

2. EXPERIMENTAL

VO₂ thin films have been obtained on c-cut sapphire substrates by electron beam evaporation of a vanadium target under a reactive oxygen atmosphere¹⁵. The electrical resistivity variation across the MIT of the obtained films were recorded during heating/cooling cycles (between 25° and 90°C) by using a current-regulated thermoelectric element (Peltier) and a two- or four-point electrical recording set-up. Figure 1a show the typical temperature-dependent hysteresis of the two-point square resistance for a 100-nm thick VO₂ film obtained on a 20x 20 mm² sapphire substrate. One may observe a drastic change of the film conductivity, by more than four orders of magnitude (conductivity in the insulating state, at 25°C of $\sigma_i = 2.12$ S/m, and conductivity in the metallic state, at 95°C of $\sigma_m = 1.23 \times 10^5$ S/m), as the sample temperature pass across the MIT transition temperature around 68°C.

Further on, in order to evaluate their high-frequency electrical and optical switching performances, VO₂ layers were integrated as simple planar two-terminal electrical devices within 50-Ω coplanar wave guide (CPW) transmission lines topologies, as illustrated in Figure 1b. In this case, the two parts of the discontinued CPW signal line were connected through a VO₂ pattern having a width of 60 μm and lengths g with values between 3 and 40 μm. The devices were realized in a clean room environment using classical micro-fabrication techniques (VO₂ patterning using photolithography wet etching and metallic electrodes fabrication (Ti/Au (30/300 nm) using optical lithography and e-beam deposition)^{4,14}.

The current-voltage (I-V) characteristics of the fabricated switches were recorded using a simple electrical circuit including the VO₂ device in series with a resistance (R_s) and a source meter (Keithley 2612A). Alternatively, the voltages across the VO₂ switch and of the series resistance were recorded using a large bandwidth oscilloscope (Tektronik DPO7254).

Figure 1. (a) Typical temperature variation of the surface (square) resistance for a 100-nm thick VO₂ film obtained on a c-cut sapphire substrate and (b) coplanar waveguide (CPW) topology of an RF switch integrating a VO₂ pattern within the signal line ($g = 20$ μm).

2. RESULTS AND DISCUSSIONS

2.1 Electrical and high-frequency performances of the VO₂-based devices

The electrical activation of MIT (E-MIT) was intensively studied in VO₂ films^{1,2,4,9,10} since it occurs on fast time-scales (down to few nanoseconds) and offer a higher degree of integration compared to the temperature-induced MIT⁹.

Figure 2a shows the typical non-linear current-voltage (I-V) characteristics of two SPST devices integrating VO₂ patterns with dissimilar lengths g of 10 μm and respectively 20 μm (gap separating the two parts of the signal line in the CPW device). As observed, for both type of devices, the increase of the voltage applied in the control circuit induced a clear E-MIT within the VO₂, marked by a sudden increase in the current flowing through the device and a decrease of more than four orders of magnitude of the overall resistance of VO₂ devices. The specific threshold voltages required for MIT activation are $V_{th1} \approx 13$ V and $V_{th2} \approx 16$ V, for devices with VO₂ lengths of $g_1 = 10$ μm and $g_2 = 20$ μm, respectively (red, respectively, blue I-V curves on Figure 2a). We may also notice a marked electrical hysteresis of the devices' I-V characteristics, which can be explained by thermal effects associated with Joule heating due to high values of the

currents flowing through the VO₂ after the insulator-to-metal transition. The threshold voltage values can reach values as low as several volts for devices with lengths g of several microns or below⁹.

Figure 2. (a) Typical current-voltage (I-V) curves of RF switches integrating 10- and 20- μm length VO₂ patterns showing electrical activation of the MIT with dissimilar voltage thresholds and (b) visualization of the metallic VO₂ filament appearing within the VO₂ pattern for applied voltages higher than the MIT threshold voltage.

The sequential optical images of the VO₂ pattern during the voltage-controlled insulator-to-metal transition of the material indicates the appearance of a metallic-VO₂ filament¹⁷. The metallic filament appears at the E-MIT threshold voltage (V_{th}) and its width is increasing with further increase of the applied voltage (to values superior to V_{th})¹⁷. As the applied voltage is lowered, the filaments decreases in width and it disappears for voltage threshold corresponding to the reverse metal-insulator transition in the material.

The broadband RF performances of the fabricated CPW devices were measured in the frequency range from 100 MHz to 40 GHz using a vectorial network analyser (ZVA Rohde& Schwarz) and ground-signal-ground (GSG) probes. Figure 3 presents the measured S parameters (S_{11} - reflection coefficients and S_{21} - transmission parameters) of two SPST switches with $g_1=10\ \mu\text{m}$ (red curves) and $g_2=20\ \mu\text{m}$ (blue curves), respectively, for both insulating (Figure 3a, at 25°C) and metallic (Figure 3b, at 95°C) VO₂ states. Besides the thermal activation of the MIT in the devices, additional measurements (not shown here) were done by electrically activating the devices, at room temperature. In this case, the VO₂ patterns were electrically switched to their metallic state using external dc bias decoupled from the RF signal using bias Ts.

Figure 3. Measured reflection (S_{11}) and transmission (S_{21}) S parameters of the RF switches for VO₂ patterns with 10- and 20- μm lengths at (a) 25°C (RF switch in the OFF, blocking state) and (b) at 90°C (RF switch in the ON, transmitting state)

As observed on the data represented on Figure 3, in the OFF state (VO_2 insulator at 25°C), the SPST switch with $g_1=10\ \mu\text{m}$ (red curves) shows good isolation level, better than 18 dB in the whole frequency band (100MHz-40 GHz), while the isolation is increased to values below 20 dB for the CPW devices with $g_2=20\ \mu\text{m}$ (blue curves). In the ON state (VO_2 in the metallic state through heating at 95°C), both devices show insertion losses lower than 0.8 dB in the same frequency range. As expected, the insertion losses for the CPW device integrating a VO_2 pattern with $g_1=10\ \mu\text{m}$ are lower, better than 0.5 dB over the complete measured frequency range.

The measured performances of the RF switches and their modeling using a simple equivalent electrical model (R_{ON} , resistance on the ON state when VO_2 is metallic and, R_{OFF} , resistance on the OFF state in parallel with a capacitance (C_{OFF} , capacitance in OFF state) when VO_2 is insulator) allow to extract their figure of merit ($\text{FOM} = C_{\text{OFF}} * R_{\text{ON}}$ expressed in fs) which is describing typical performances of RF switching devices. Typical FOM values of devices with different VO_2 lengths (g) lie in the range 25-50 fs which are several times better than the FOMs of current semiconductor-based RF commercial switching technologies (between 150 and 300 fs). The switching times of the electrically induced MIT on the VO_2 -CPW devices (measured using an applied square-type waveform on the CPW switches) shows rising times around 20 ns (not reported here).

However, it is interesting to note that the performance of the electrical activation of the devices is limited because the MIT in the VO_2 pattern is initiated by the appearance of a conductive filament (metallic VO_2 surrounded by the insulating parts, as illustrated in Figure 2b) which widens with the rise of the voltage and may not fully cover the width of the VO_2 pattern integrated on the CPW signal line. For voltages higher than the MIT threshold voltage but close to the threshold voltage values, this is resulting in an overall resistance of the VO_2 pattern which is not small enough (compared to that obtained by direct heating of the device – when the entire VO_2 pattern is switched to its metallic state) and induces higher RF losses than the thermal activation.

From this point of view, in order to circumvent electrical activated MIT with large voltage-current combinations (which will eventually enlarge the metallic filament to the whole VO_2 pattern area), optical activation of the VO_2 patterns within the CPW devices is a very interesting alternative. This may allow uniform, lower-energy, whole-area activation of MIT within the VO_2 patterns and will minimize RF losses in the ON-state of the RF switch.

2.2 Optical-induced metal-insulator transition in VO_2 devices

In order to evaluate the optical activation of MIT, we directly irradiated the 10- μm length VO_2 pattern of the CPW device with single laser pulses coming from the end tip of an optical fiber conveying laser pulses from a high-power laser diode operating at an optical wavelength of 980 nm. The laser diode is able to deliver laser pulses with temporal widths between 10ns and 30 μs and mean powers between 15 mW and 140 mW at pulse repetition rates up to 500 kHz (Figure 4a). During optical irradiation of the VO_2 pattern, the overall resistance of the device is monitored using a simple electrical circuit in which the CPW was integrated in series with a dc source (delivering a constant voltage of 2 V) and a series resistance of $R_s=150\ \Omega$. The optical fiber and the electrical probes are positioned on a specific CPW device using piezoelectric manipulators with nanometer-scale resolution (Imina Technologies, Switzerland).

Figure 4. (a) Photography of the implemented set-up and (b) the equivalent electrical circuit used to evaluate the electrical response of the two-terminal RF switch during optical irradiation of the VO_2 pattern.

The optical irradiation of the VO₂ pattern in the CPW device is triggering the MIT for laser pulses as short as 25 ns and energies between 130 and 170 nJ/pulse. As indicated on the schematic electrical circuit in Figure 4b, the current modification in the electrical circuit subsequent to the optical-induced MIT (drastic modification of the VO₂ pattern resistance and consequently, of the current in the circuit) was recorded on a fast oscilloscope as the voltage variation on the series resistance (V_{RS}) during laser pulsed irradiation of the VO₂ pattern. Figure 5a and respectively Figure 5b, are illustrating a closer optical view of the measured device during laser OFF and laser ON continuous-wave operation and the associated voltage drop on the series resistance, respectively.

Figure 5. (a) Optical microscopy image of a device under test during laser OFF/ laser ON operation, (b) voltage V_{RS} recorded over the series resistance R_S in Figure 4a during the two extreme ON/ OFF irradiation states (in CW mode) and (c) typical electrical response of the device (V_{RS} , black curve) when irradiated with a single laser pulse having a temporal width of 1 μ s (red curve).

Also plotted on Figure 5c is the typical electrical response (expressed as the V_{RS} voltage variation) of the device subsequent to optical irradiation of the VO₂ pattern using a 1- μ s long single laser pulse (black curve) along with the recorded temporal shape of the delivered laser pulse having an energy of 140 nJ (red curve).

The recorded electrical response of the CPW device during optical activation of MIT in VO₂ allows us to evaluate MIT response times in the range 10-15 ns, depending on the width of the applied laser pulses and their energy. As visible on Figure 5c, the time it takes the device to recover its initial OFF state (VO₂ back to its insulating state after removing the optical excitation) are much longer than the rise times (typical values between 500 and 1500 ns) and restrain the maximum repetition frequencies of the pulsed dynamic ON/OFF operation of the optically-activated switch to around 500 kHz. On-going investigations show that the values of the insulating state recovering times depend on the incident optical pulse width, on the RC time constant of the electrical recording circuit (device capacitance and series resistance values dependence) and on the thermal resistance of the overall device.

The reliability of the optical switching of a 10- μ m long VO₂-based CPW device was evaluated by continuously applying trains of optical pulses of different widths and energies, at repetition frequencies between 100 kHz and 400 kHz. Figure 6 shows typical records of the voltage variations on the series resistance upon irradiation of the VO₂ pattern using trains

of 100, 300 and 550 laser pulses (500-ns width) at 200 kHz, as well as a detailed view of the pulsed electrical response of the device taken during irradiation with a train of 550 laser pulses. The optical activation of the VO_2 is extremely stable and reliable; we were able to perform more than 1 billion switching cycles without damaging the material nor the CPW device.

Figure 6. (a) Voltage variation on the series resistance during optical activation of a 10- μ m long VO_2 pattern within the RF device using trains of 100, 300 and 550 laser pulses (500-ns width, 200 kHz) and (b) zoom-in of the electrical response corresponding to the pink-colored area in figure (a).

3. CONCLUSIONS

We presented the design, fabrication, and high frequency characterization of RF switches based on VO_2 integration in CPW lines with very good RF performances on a broad frequency band. The VO_2 -based devices were actuated between their ON and OFF state on nanosecond timescales, using both electrical and optical short laser pulses. The investigation

of their RF properties show that the devices present high OFF-state isolation, high resistivity ratio ($R_{\text{OFF}}/R_{\text{ON}}$), low insertion losses, and very good figures of merit. The optical activation scheme of VO₂ we are proposing here may be relevant for applications in which the RF interference commonly associated with extensive electrical control circuitry of RF devices (e.g. antennas and antenna networks) must be avoided and is emerging as a promising solution for reconfiguration and agility applications in the millimeter-waves to THz frequencies range.

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