Exploiting the semiconductor-metal phase transition of VO₂ materials: a novel direction towards tuneable devices and systems for RF-microwave applications

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1. Introduction

Increasing demands for reconfigurable microwave and millimeter-wave circuits are driven for their high-potential integration in advanced communication systems for civil, defense or space applications (multi-standard frequency communication systems, reconfigurable / switchable antennas, etc.). A wide range of tunable and switchable technologies have been developed over the past years to address the problems related to the overlapping of the frequency bands allocated to an ever-increasing number of communication applications (cellular, wireless, radar etc.). Usually, the reconfiguration of such complex systems is realized by using active electronics components (semiconductor-based diodes or transistors) (Pozar, 2005) or, at an incipient stage, RF MEMS (Micro-electro-mechanical systems)-based solutions (Rebeiz, 2003). However, the performances of these systems are sometimes limited by the power consumption and non-linear behaviour of the semiconductor components or by the yet-to-be-proved reliability of the MEMS devices (switches or variable capacitors).

Current research towards the development of smart multifunctional materials with novel, improved properties may be a viable solution for realizing electronic devices and/ or optical modules with greater functionality, faster operating speed, and reduced size. Smart materials are those materials whose optical and electrical properties (transmittance, reflectance, emittance, refractive index, electrical resistivity etc.) can be controlled and tuned by external stimuli (applied field or voltage, incident light, temperature variation, mechanical stress, pressure etc.). In the RF-microwave fields, materials that are relevant towards the fabrication of tuneable components (resistors, capacitors, inductors), can be classified according to their tuneable properties as: *tuneable resistivity materials* (semiconductors, phase change materials), *tuneable permittivity materials* (ferroelectrics,

liquid crystals, pyrochlores, multiferroics) or *tuneable permeability materials* (ferromagnetics, multiferroics etc.) (Gevorkian, 2008). They can be used to build intelligent components for a broad range of applications: phase shifters/ modulators, delay lines, switches, filters and matching networks, tuneable loads, agile antennas, sensors, detectors etc.

Among the most attractive class of smart materials are those exhibiting a phase transition or a metal- insulator transition. The metal-insulator transition is a large area of research that covers a multitude of systems and materials (chalcogenides, colossal magnetoresistance manganites, superconducting cuprates, nickelates, ferroelectrics, etc.) (Mott, 1968; Edwards et al., 1998). In particular, certain transition metal oxides exhibit such phase transition (Rice & McWhan, 1970), and among these, the vanadium oxide family (V_2O_5 , V_2O_3 , VO_2) shows the best performance, in particular, presenting a noticeable resistivity change between the two phases. Among these, vanadium dioxide, VO_2 , has been studied intensely in the last decade because of its large, reversible change in its electrical, optical and magnetical properties at a temperature close to room temperature, of $\sim 68^\circ\text{C}$ (Morin, 1959) which makes it a potential candidate for introducing advanced functionalities in RF-microwave devices.

Within the present chapter, we want to offer an insight on the *amazing properties of the VO_2 materials* (focusing on the electrical ones) and to *give practical examples of their integration in advanced adaptive devices* in the RF-microwave domain, as developed in the last years at the XLIM Institute in collaboration with the SPCTS laboratory, both from CNRS/ University of Limoges, France (Crunteanu et al., 2007; F. Dumas-Bouchiat et al., 2007, 2009, Givernaud et al., 2008).

We will focus in a first step, on the fabrication using the laser ablation (or the pulsed laser deposition -PLD) method of the VO_2 thin films, on its structural, optical and electrical characterization (speed and magnitude of phase transition induced by temperature or an external electrical field). In a second step we will show the practical integration of the obtained VO_2 films in RF- microwave devices (design, simulation and realisation of VO_2 -based switches and tuneable filters in the microwave domain etc.) and we will conclude by presenting the latest developments we are pursuing, namely the demonstration of VO_2 -based, current-controlled broadband power limiting devices in the RF- microwave frequency domains.

2. VO_2 material properties and applications

As mentioned before, vanadium dioxide is one of the most interesting and studied members of the vanadates family performing a metal-insulator (or, more correctly, a semiconductor to metal phase transition- SMT) (Morin, 1959; Mott, 1968). At room temperature (low temperature state) VO_2 is a semiconductor, with a band gap of ~ 1 eV. At temperatures higher than 68°C (341 K) VO_2 undergoes an abrupt transformation to a metallic state, which is reversible when lowering the temperature below 65°C (VO_2 becomes again semiconductor). This remarkable transition is accompanied by a large modification of its electrical and optical properties: the electrical resistivity decreases by several orders of magnitude between the semiconductor and the metallic states while the reflectivity in the near-infrared optical domain increases (Zylbersztein & Mott, 1975; Verleur et al., 1968). The reversible SMT transition can be triggered by different external excitations: temperature, optically (Cavalleri et al., 2001, 2004, 2005; Ben-Messaoud et al., 2008; Lee et al., 2007), electrically- by charge injection (Stefanovich et al., 2000; Chen et al., 2008, Kim et al., 2004,

Guzman et al., 1996, Dumas-Bouchiat et al., 2007) and even pressure (Sakai & Kurisu, 2008). Recent studies showed that the electrically- and optically- induced transitions can occur very fast (Stefanovich et al., 2000; Cavalleri et al., 2001-2005) (down to 100 fs for the optically- triggered ones (Cavalleri et al., 2005)) and that the transition is more typical of a rearrangement of the electrons in the solid (electron- electron correlations) than it is an atomic rearrangement (crystalline phase transition from semiconductor monoclinic to a metallic rutile structure).

Although a large number of studies have been devoted to the understanding of the SMT in VO₂, there is still no consensus concerning the driving mechanisms of this phase transition (Pergament et al., 2003; Laad et al., 2006, Qazilbash et al., 2007, Cavalleri et al., 2001). The two mechanisms believed to be responsible for the phase transition (the Peierls mechanisms- electron-phonon interactions and the Mott-Hubbard transition – strong electron-electron interactions) are still elements under debate (Morin, 1959; Mott, 1968; Cavalleri et al., 2001, Stefanovich et al., 2000, Pergament et al. 2003, Kim, 2004; Kim, 2008).

The transition temperature of the VO₂ layers can be shifted to lower temperatures e.g. by applying an electric field or an incident light beam to a planar two-terminal device (Kim et al., 2004; Lee et al., 2007, Qazilbash et al., 2008, Chen et al., 2008). It is believed that an electric field application to VO₂ or an incident beam influences the electron or holes concentrations resulting in a shift of the transition temperature. According to the Mott-Hubbard mechanism (Laad et al., 2006), the SMT transition should be driven by the increase in electron concentration (once the electrons reach a critical concentration, the VO₂ pass from semiconductor to metallic). Also, the transition temperature of the VO₂'s SMT can be increased or decreased by doping with metals like W, Cr, Ta or Al (Kitahiro & Watanabe, 1967; Kim et al., 2007). VO₂ has a high voltage breakdown, which can be exploited for transmission of high power levels in microwave devices.

In the last years, an ever increasing number of papers have been published and discussed VO₂-based applications, most of which are on microbolometers applications (Yi et al., 2002; Li et al., 2008), smart thermochromic windows (Manning et al., 2002), spatial light modulators (e.g. Richardson and Coath, 1998; Jiang and Carr, 2004; Wang et al., 2006) or electrical switches development (thin films and single-crystal structures) (e.g. Guzman et al., 1996; Stefanovich et al., 2000; Qazilbash et al., 2007; Kim et al., 2004), but the functioning of the proposed devices is based mainly on the thermal activation of the MIT transition which is far more slow than the purely electric or optical- activated ones (massive charge injection or optical activation). The very few reports concerning the possible integration of VO₂ thin films in devices and systems for RF and millimetre wave applications concerns their dielectric properties in this domains (Hood & DeNatale, 1991), the fabrication of submillimeter -wave modulators and polarizers (Fan et al., 1977), of thermally controlled coplanar microwave switches (Stotz et al., 1999) and numerical simulations of VO₂-based material switching operation in the RF-microwave domain (Dragoman et al., 2006). The operating frequency for VO₂-based switches was estimated to be beyond 1 THz (Stefanovich et al., 2000), which makes them very attractive for realizing broadband devices in the millimetre-wave domain.

In the last few years we successfully integrated PLD-deposited VO₂ thin films in several types of components and more complex devices such as thermally and electrically-activated microwave switches (Crunteanu et al., 2007; Dumas-Bouchiat et al., 2007 and 2009), tunable band stop filters including VO₂-based switches (Givernaud et al., 2008) and recently, we

proposed an original approach for the design and fabrication of self-resetting power limiting devices based on microwave power induced SMT in vanadium dioxide (Givernaud et al., 2009). As an illustration of our current activities towards the integration of VO₂ layers in RF-microwave (RF- MW) devices, we will present the design, fabrication and characterization of thermally activated MW switches and their integration in a new type of thermally triggered reconfigurable 4-bit band stop filter designed to operate in the 9- 11 GHz frequency range.

3. PLD deposition and structural, optical and electrical characterization of the VO₂ thin films

Several deposition methods have been proposed for fabrication of VO₂ thin films: sputtering, evaporation pyrolysis or chemical reaction techniques (Hood & DeNatale, 1991; Stotz et al., 1999; Manning et al., 2002; Li et al., 2008 etc.). According to the multivalency of vanadium ion and its complex oxide structure (Griffiths & Eastwood, 1974), numerous phases with stoichiometries close to VO₂ can exist (from V₄O to V₂O₅) and the synthesis of phase pure VO₂ thin films is an important challenge. Reactive pulsed laser deposition (PLD) is a suitable technique for obtaining high-purity oxide thin films (Chrissey & Hubler, 1994; Eason, 2007), very well adapted for obtaining the stoichiometric VO₂ layers. However, careful optimisation of the working parameters is necessary to obtain thin films of the pure VO₂ stabilized phase without any post-treatment.

Fig. 1. Photography of the PLD set-up showing schematically the inside of the deposition chamber (left-hand side) and the expansion of the plasma plume towards the substrate after the laser pulse (right-hand side).

In our case, VO₂ thin films were deposited using reactive pulsed laser deposition from a high purity grade (99.95%) vanadium metal target under an oxygen atmosphere. The experimental set-up (picture shown in Fig.1) was described elsewhere (Dumas-Bouchiat et al., 2006) and is based on an excimer KrF laser (with a wavelength of 248 nm and a pulse duration of 25 ns), operating at a repetition rate of 10 Hz. The laser beam is focused on a rotating target in order to obtain fluences (i.e. energies per irradiated surface unit) in the order of 5 to 9 J/cm². The plasma plume expands in the ambient oxygen atmosphere (total

pressure in the chamber maintained at 2×10^{-2} mbar). Since it has a relatively low lattice parameter mismatch (4.5%) as compared to VO₂ monoclinic phase, monoclinic Al₂O₃(C) is a good candidate to deposit mono-oriented VO₂ films (Garry et al., 2004). The substrate is heated by an halogen lamp at about 500°C and the deposition duration is changing from 10 to 45 minutes leading to thickness in the range 100 - 600 nm. VO₂ thin films have been also deposited on sapphire R-type substrates (Al₂O₃(R)), quartz or 100 Si substrates (bare or oxidized with a 1- μ m thick layer of SiO₂).

Irrespective on the substrate we used, the obtained films show a smooth surface with very low-density or no particulates at all, as indicated by scanning electron microscopy analysis, see Fig. 2a. Their morphology (as revealed by atomic force microscopy, AFM, Fig. 2b) consists of compact quasispherical crystallites with typical dimensions (root mean square roughness) between 5 and 15 nm. The non-dependence of film morphology on the substrate nature may be an indication that the growth mechanism is governed mainly by the laser beam/ target interaction.

Fig. 2. a) SEM image of a VO₂ thin film growth on a sapphire substrate showing a smooth surface and b) AFM image obtained on a VO₂ film (75-nm thickness) onto a sapphire R substrate showing compact crystallites.

Fig. 3. Typical XRD scan for a 200-nm thick VO₂ thin film deposited on an Al₂O₃(C) substrate showing characteristic peaks ((020) and (040) of the monoclinic phase of VO₂).

X-Ray diffraction -XRD investigations (in θ , 2θ configuration) performed on $\text{VO}_2/\text{Al}_2\text{O}_3(\text{C})$ thin films reveal two peaks located near 40.2° and 86.8° corresponding respectively to the (020) and (040) planes of the monoclinic VO_2 phase. In certain cases, and especially for amorphous substrates (SiO_2/Si substrates), depending on the deposition parameters, a peak appears near 28° corresponding to the (011) planes of VO_2 with an orthorhombic structure (Youn et al., 2004).

3.1 Temperature-induced SMT of VO_2 thin films

For the obtained VO_2 films we recorded the variation of their electrical optical and properties (resistivity and optical transmission variation) with the applied temperature in order to rapidly assess the amplitude of their temperature-activated SMT transition.

The electrical resistance/ resistivity of the VO_2 thin films was recorded in the $20\text{-}100^\circ\text{C}$ temperature range using a two-terminal device (two metallic contacts deposited nearby on a rectangular VO_2 pattern). A typical resistance hysteresis cycle (heating- cooling loop) of a 200-nm thick VO_2 thin films deposited on a C-type sapphire substrate can be observed in Fig. 4 (the VO_2 pattern between the two measurements electrodes was, in this case, $70\text{ }\mu\text{m}$ long $\times$ $45\text{ }\mu\text{m}$ wide and 200 nm thick). One may observe a huge change in its resistance as the temperature is cycled through the phase transition ($R \sim 450\text{ k}\Omega$ at 20°C down to $R \sim 75\text{ }\Omega$ at 100°C). The width of the hysteresis curve (heating- cooling cycle) is very small: the transition occurs in the $72\text{-}74^\circ\text{C}$ range when heating the sample (transformation from semiconductor to metal) and in the $65\text{-}68^\circ\text{C}$ range when cooling down at room temperature, and is witnessing on the high quality of the obtained material.

Fig. 4. Resistance variation with temperature for a VO_2 film (two terminal device of $70\text{ }\mu\text{m}$ long, $45\text{ }\mu\text{m}$ wide and 200 nm thick) fabricated by PLD on a C-type sapphire substrate

The optical transmission measurements of VO_2 layers on different substrates as a function of the temperature were done in the UV-visible- mid-IR regions of the spectrum using a Varian Carry 5000 spectrophotometer equipped with a sample heater. They were recorded for different temperatures in the $20\text{-}100^\circ\text{C}$ domain. As observed on Fig. 5, the VO_2 films

deposited on Al₂O₃ (R) and on SiO₂/ Si substrates showed a very sharp phase transition witnessing of abrupt change (transmission change factors between 4 and 8) of its optical properties (drastic modification of its refractive index and absorption coefficient). One may notice on the graph on Fig. 5a that the temperature- dependent transmission curves intersect in a particular point, the isosbestic point (at ~850 nm) where the transmittance is constant for all temperatures (Qazilbash et al., 2007).

Fig. 5. Optical transmission spectra vs. temperature for 50-nm thick VO₂ films made by PLD on R-type sapphire substrates (a) and 1-μm thick SiO₂/ Si substrate (the oscillations visible on these spectra are interference patterns due to the SiO₂/ Si stack layers)(b).

We also investigated the reflectivity variation of the VO₂ films versus the temperature. Typically, a substrate covered with a VO₂ thin layer was placed on a heating stage and the optical power of a reflected fiber laser beam (at 1550 nm) directed at almost normal incidence onto the film surface was recorded during temperature variation in the 20-100°C domain. On Fig. 6 is presented a typical hysteresis cycle of film's reflectivity (heating-cooling cycle). The VO₂ films showed a very sharp, abrupt phase transition that occurs

irrespective of the used substrate or of their thickness. As in the case of the electrical resistivity measurements, the width of the hysteresis curve is very small.

Fig. 6. Hysteresis cycle of reflectivity (at 1550 nm) vs. temperature for a 75-nm thick VO₂ film made by PLD on C-type sapphire substrate showing the sharp phase transition of the VO₂ material.

3.2 Electrically- induced SMT of VO₂ thin films

The proof of concept of thermally induced SMT of VO₂ thin films for realising microwave (and optical) switching devices shown above represents already an innovative, interesting field of research both from theoretically and practical points of view. However, the electrically driven SMT of the VO₂ material will results in more practical devices (without the need of a additional temperature source for the phase transition activation) that, theoretically, can be activated several orders of magnitude faster (Mott, 1968; Cavalleri et al., 2001; Stefanovich et al., 2000; Kim et al., 2004).

We therefore initiated investigations for evaluating the electrically induced phase transition of VO₂ thin films integrated in two-terminal switching devices. The VO₂ pattern is included in an electrical circuit (Fig. 7a) with a c.c. voltage source (applied voltage, V_{ap}), an amperemeter (measuring the current in the circuit, I) and a resistor (R_s , with typical values between 100 and 1500 Ω) for limiting the overall current in the circuit since high values of the current may damage the VO₂ switch. The first results (I - V_{ap} and I - V_{VO_2} characteristics) of the electrically actuated VO₂- based two-terminal device (rectangular pattern, 40- μ m long, 95- μ m wide and 200 nm thick) are presented on Figs. 7 b, c. It may be seen that at a given threshold voltage (V_{ap} between 11 and 14 V for the c.c. voltage source, and $V_{VO_2} \sim 10.5$ to 13 V for the voltage on the VO₂ circuit, depending on the R_s value) the current increase abruptly, indicating that the resistivity of the VO₂ layer decreased. This phenomenon is indicative on the onset of the phase transition, VO₂ passes from a high resistive state (semiconductor) in a low-resistive one (it becomes metallic).

Fig. 7. a) Electrical circuit set-up for investigating the Electrically- induced SMT transition of a two terminal switching device based on a VO₂ thin film (200-nm thick on C-type sapphire); b) I- V_{ap} hysteresis characteristic as the V_{ap} is swept between 0 and maximum of 30V and backwards and c) the typical S-shape of the I- V_{VO2} characteristic of the device.

The nonlinear, S-shaped, negative differential resistance (NDR) I- V_{VO2} characteristic, typical for the VO₂ material (and whose shape can be tuned with external applied temperature) is of high interest from the viewpoint of fundamental physics as well as of a broad range of applications (NDR based oscillators, transistors, filters etc.).

The device remains in the activated state as long as the voltage or the current is maintained in the circuit. For evaluating the switching time of the electrically induced transition we used a similar activation schema (Fig. 8a) but including an a.c. voltage actuation with a square-type waveform (voltage pulses for which the temporal width were varied from 1 to 20 μm).

Fig. 8. a) Set-up for electrical activation of the SMT transition and evaluation of the switching time of a VO₂-based two-terminal switch b) applied squared waveform (16 V amplitude, 1.5 μs in width) and the voltage variation through the VO₂ switch (in series with a resistor having $R_s = 278 \Omega$) showing installation of the VO₂'s SMT with activation times Δt which varies between 100 and 250 ns.

As indicated in Fig. 8 b, c, preliminary results indicate switching times values as low as several hundreds of nano-seconds, which are, however, situated well above the electronically induced VO₂ transition (supposed to occur in the ps domain).

Although the theoretical calculations for a current-induced temperature initiation of the SMT transition (by the Joule heating effect) on the tested device lies in the order of the micro-second scale time (higher than the switching times we recorded), it is premature to assess on a purely electrical-induced phase transition (by charge injection). More likely we recorded a switching time describing a mixture of the two potentially present mechanisms (Joule effect heating and charge injection). Nevertheless, the key point of these experiments is that the switching time values are better than those of devices employing fast MEMS-based solutions (Lacroix et al., 2007) and not far from the switching times values of the semiconductors currently used in millimeter domain-switching devices.

We should point out that the electrical activation of VO₂ thin films is also accompanied by changes in their optical properties, easily perceived using optical microscopy and recorded using a CCD camera, as reflectivity change periodically with the applied a.c. signal. These findings are currently exploited in our group for fabrication of variable reflectivity micro mirrors and attenuators in the optical domain for high-speed modulators in novel laser systems (results not reported here).

To resume the preliminary results presented above we may say that the VO₂ is a very interesting and exciting phase transition material. Its electrical and optical properties may be tuned in a static or dynamical way by external factors such as the temperature or an applied electrical field or voltage. These results were further exploited for the realization of rapid electrically switching of microwave coplanar waveguide (CPW) lines or the fabrication of band-stop-type MW filters.

4. Integration of VO₂ thin films in microwave switches and filters

The enormous resistivity change (3 to 4 order of magnitude) of the VO₂ material undergoing the SMT induced by the temperature or by an applied voltage was exploited to fabricate and characterize simple microwave switches based on a coplanar microwave waveguide integrating VO₂ thin films. We obtained temperature activated switching functions (in both shunt and series configurations) with relatively low losses and more than 25 dB transmission variations between the ON/OFF states, on a very large bandwidth (50 MHz–35 GHz) (Crunteanu et al., 2007; Dumas-Bouchiat et al., 2009). The concept was successfully implemented for more complex devices, such as tuneable band stop filters operating around 10 GHz in the microwave frequency domain (Givernaud et al., 2008).

4.1 Microwave switching based on VO₂ films two terminal devices

In the followings we will present a novel concept of VO₂-based electrical switch by using the discrete (and local) thermal activation of a VO₂ two-terminal device using a miniature heating element. The micro-heater is based on a thin-film resistor fabricated from a Ni-doped tetrahedral carbon layer (Ni:ta-C). Nickel-doped ta-C layers are currently used in our laboratory and efficiently integrated in radio frequency micro electro mechanical systems (RF MEMS) and in other tunable components (Orlianges et al., 2005). These thin films allow the realization of localized, high value, planar, easily patterned resistances, leading to significant improvement of insertion losses of MEMS switches integrated in electronic devices. Such thin-film resistors are often used under high value of electrical current, which generate important heating of these devices. Our previous investigations on ta-C layers doped with 5%- 30% wt. Ni showed that the layers preserve their integrity for current

densities as high as $1.5 \cdot 10^5 \text{ A/cm}^2$ (Orlianges et al., 2004). This characteristic of the Ni:ta-C layers can be exploited for fabrication of localized, micrometer-range heating elements which may be used to discretely activate VO_2 -based two terminal switches (the important amount of heat generated into the Ni:ta-C layers will be transmitted to the VO_2 patterns placed underneath). The amount of the heat generated by the micro heater element can be adjusted by changing the dimensions and the doping level of the Ni:ta-C pattern. The design of a fabricated VO_2 -based switch which can be activated by the heat generated in a Ni:ta-C thin film is presented in the optical microscope image on Fig. 9 a.

Fig. 9. a) Optical microscopy image of a VO_2 -based two terminal switch (400- μm long, 200- μm wide, 200-nm thick pattern between two gold electrodes) which is activated by the current induced heating in a 10% wt. Ni:ta-C pattern situated above it (340- μm long, 150- μm wide and 100-nm thick) and b) optical images showing the sequential activation (phase transition) of the underneath VO_2 layer when applying periodical squared voltage pulses (80V amplitude, 1Hz) on the Ni:ta-C pattern (VO_2 -S-semiconducting phase and VO_2 -M – the mettalic state of the VO_2 layer).

The device was fabricated in a clean room environment using classical micro fabrication technology. The 200-nm thick VO_2 films were deposited using PLD from a vanadium target in oxygen atmosphere on C-cut sapphire substrates (500- μm thickness) in the conditions described above. The VO_2 layers were further patterned using optical lithography and wet

etching for defining the rectangular patterns. It follows the partial masking of the substrate with a photoresist layer for deposition of the Ni:ta-C layers (~100-nm thick) precisely above the VO₂ patterns (the lift-off technique). The nickel doped ta-C films have been deposited under high vacuum by KrF laser ablation of alternating C and Ni targets at ambient temperature (Orlianges et al., 2004). At the end, we fabricated the metallic electrodes: a Ti/Au layer (6-nm/ 1- μ m thick Ti is used as adhesion layer) is deposited using thermal evaporation; the shape of the electrodes are defined by photoresist masking using optical lithography followed by the partial wet etching of the Ti/ Au layer. We tested different pattern dimensions for the VO₂ switch (from 200 to 400- μ m long and 100 to 200- μ m wide) and for the heating Ni:ta-C thin film resistors (100 to 350- μ m long and 50 to 150- μ m wide). For the device shown in Fig. 9 a (VO₂ pattern of 400- μ m long, 200- μ m wide, 200-nm thick pattern between the two metallic electrodes), when applying a current (up to 10 mA) to the Ni:ta-C heating element (340- μ m long, 150- μ m wide, with an overall resistance of ~11 k Ω) the heat generated in the micro-heater will dissipate to the underneath VO₂ layer and will raise its temperature above the SMT's transition temperature (around 68°C). The VO₂ will therefore pass from a semiconductor to a metal state. As in the case of an optical switch, the transition is easily observed using the optical microscopy as clear changes of the VO₂ layer's reflectivity. These sequential reflectivity changes were recorded using a CCD camera (Fig. 9 b) as we applied to the micro heating layer (Ni:ta-C) a pulsed periodical squared signal (80V amplitude, 1Hz). The onset of the VO₂'s phase transition was also recorded electrically by monitoring the resistance of the two-terminal device as a c.c. voltage was progressively applied on the Ni:ta-C heater (Fig. 10).

Fig. 10. VO₂'s two-terminal device transversal resistance versus the voltage applied on the Ni:ta-C heating resistance: heating phase (red), cooling phase (blue)

One may easily noticed the great variation of the VO₂'s resistivity (onset of the SMT) as the Ni:ta-C element dissipate the resistive heating. Work is in progress in order to simulate the heating transfer processes in the overall device, which will allow for optimum design in term of lowering the power consumption. The obtained thermal switching device allows for discrete, localized activation of micrometer-sized VO₂ patterns and may be easily integrated

in more complex functions (filtering module), as it will be demonstrated in the next sub-chapter.

4.2 Design and performances of tuneable band-stop filters including VO₂-based switches.

We used the large resistivity change of the device presented above for realising a tuneable 4-pole band stop filter designed to operate in the 9- 11 GHz frequency range with a large signal attenuation in the attenuated band (> 20 dB) (Givernaud et al., 2008). The filter (realised in the micro strip geometry) consists in a $50\ \Omega$ transmission line coupled with four U-shaped resonators (Fig. 11). Each resonator is "closed" by a VO₂-based pattern which can be independently activated from the semiconductor to the metallic phase by the Ni:ta-C thin film micro heater. At room temperature, the VO₂ patterns are insulating (VO₂ pattern resistance of $98\ \text{k}\Omega$), the resonators are "opened" and each of them will introduce a specific absorption band in the transmission spectrum of the filter (Fig. 13 a). The design of the filter was done using the ADS Momentum simulator and the dimensions and position of each of the resonators (position and distance from the transmission line) was optimised in such a way that the sum of each absorption band result in an broad absorption band between 10 and 11 GHz while maintaining a high signal attenuation (> 20 dB), as visualized in Fig. 13 a.

Fig. 11. Design of the four-pole band stop filter that can be discretely tuned by thermally activated each of the VO₂-charged resonators; the insert shows the design of the VO₂-based switch (activated by a Ni:ta-C pattern) which was adapted to the filter's design.

When individually activated, the metallic VO₂ pattern (resistance of $78\ \Omega$) will electrically closed its corresponding U-shaped resonator. The design of the filter (dimensions, resonators dimensions etc.) was done in such a way that the absorption band of the activated resonator would be then shifted far away from the operation frequency band of the filter. The response of the filter will change: shift of the absorption band (tuneability),

bandwidth decrease and even disappearance of the attenuation band (Fig. 13 b when all the resonators are activated). This concept was already applied (Givernaud et al., 2008; Dumas-Bouchiat et al., 2009) and results in innovative, discretely tuned filtering functions in the microwave domain.

The filter was fabricated in a clean room environment using classical micro fabrication technology in the conditions described elsewhere (Givernaud et al., 2008). The obtained device was placed using a conductive epoxy paste (for defining the ground plane of the micro strip geometry) in a metallic package and the transmission line ends are electrically connected to SMA-type connectors for measurements (Fig. 12).

Fig. 12. Photography of the realized VO₂-based four-pole filter inserted in a metallic housing and connected to SMA connectors for measuring its response.

a.

b.

Fig. 13. a) ADS Momentum simulation of the S_{21} transmission parameter for the overall filter (red curve), showing the absorption band contributions of each resonators and b) the simulated S_{21} transmission parameter of the four-pole band stop filter when the VO_2 -based resonators are "opened" (red curve, $\text{VO}_2\text{-SC}$) and "closed" (blue curve, $\text{VO}_2\text{-metal}$).

The response of the packaged filter was measured using a calibrated four-ports vectorial network analyser (VNA, HP 8722 ES) in the 7 to 14 GHz frequencies range. The measured response of the filter is presented on the graph in Fig. 14 in the two extreme cases: when all the VO_2 patterns are insulating, red curve, and when all the VO_2 patterns are activated by the Ni:ta-C micro-heating elements.

Fig. 14. Measured responses (transmission S_{21} parameter) of the four pole band stop filter, at room temperature (red curve $\text{VO}_2\text{-SC}$) and activated (blue curve, $\text{VO}_2\text{-metal}$, all of the resonators are activated)

One may notice a good agreement of the measured filter responses with the simulations (Fig. 13b). Although the operation band is shifted towards the low frequencies this can be easily corrected for future design by taking into account the deviation from the theoretical values of the materials constants used for the simulation response and by taking care to the micro fabrication tolerances). The tunability of the filter can be demonstrated by individual activation (using the micro-heaters) of specific resonators. When the VO₂-switch of two resonators, for example resonators 1 and 4 (as marked on the Fig. 11) becomes low resistive (VO₂ in the metallic state), the rejection band of the filter will change: its central frequency will shift towards higher frequencies, at 10.6 GHz and its full width at half maximum (FWHM) will lower from ~ 1 GHz to about 0.4 GHz, as shown for the simulated response on Fig. 15 a. A similar behaviour was recorded for the measured response (Fig. 15 b) although the decreasing of the rejection bandwidth was less marked.

Fig. 15. ADS Momentum simulation (a) and measurement results (b) of the four-pole band stop filter when resonators 1 and 4 (as indicated on the Fig. 11) are simultaneously activated (blue curve, compared with the initial response of the non-activated filter, the red curve).

The simultaneous activation of two others resonators (those numbered 2 and 3 on Fig. 11), leads to a displacement of the central frequency of the rejection band of the filter towards lower frequencies (measurements shown on Fig. 16) at 9.6 GHz (FWHM = 0.4 GHz).

Fig. 16. S21 transmission measurement of the four-pole band stop filter when resonators 2 and 3 (as indicated on the Fig. 11) are simultaneously activated (curve in magenta, compared with the response of the non-activated filter, the red curve and the response of the totally activated filter, blue curve).

We presented above the concept of an VO₂- based electrical switch which can be discretely activated using a Ni:ta-C micro-heating element. These resistivity-switching functions were introduced in a more complex design for fabrication of a band-stop filter with tunable absorption bands and bandwidth operating in the 9-11 GHz frequency domain. Although the device can be further optimized in for obtaining better performancesz we wanted to demonstrate that VO₂ material-based components are serious candidates for RF-microwave switching and microwave reconfigurable devices.

5. Conclusion

The VO₂ material fabricated using the PLD technique results in crystalline thin films performing sharp, high amplitude SMT phase transition and with very good electrical properties. The electrical and temperature-activated VO₂-based switches are promising devices for fabrication of tunable filters and other complex functions in the RF/ microwave domains. The results presented so far are of the state-of-the-art international level concerning the elaboration and characterization of thin films VO₂ of and their integration in practical microwave (and optical) devices. Further applications we are currently developing concerns complex broadband devices employed in the telecommunication networks in the millimeter-wave domain (3-terminal type fast switches, phase shifters, broadband power limiting devices based on microwave power induced SMT in vanadium dioxide, tunable bandpass filter that combines split ring resonators (SRRs) and vanadium dioxide (VO₂)-

based microwave switches etc.) as well as the design of optical devices for applications using miniature laser systems or optoelectronics (optical switches, optical filters, variable attenuators and modulators etc.). The realization of these new type of devices widens a new and extremely rich activity in the field of device fabrication for millimeter-wave reconfigurable systems or for integrated optics and optical communication systems.

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