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VO_2: A Phase Change Material for Micromechanics †

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Abstract: Micro- and nano-mechanical systems may take advantage from using materials having multiple functional characteristics. VO_2 is a compound characterised by a solid state phase transition (SSPT) just above room temperature, consisting in a concurrent metal-insulator transition and a change of lattice symmetry and parameters. Here, the combination of non-linear electrical response and structural changes is employed to realise a novel high-frequency mechanical actuation scheme, showing direct conversion from DC voltage to mechanical excitation in the MHz range and selective activation of the different mechanical modes of a microstructure.

Keywords: mechanical oscillators; Vanadium dioxide; MEMS

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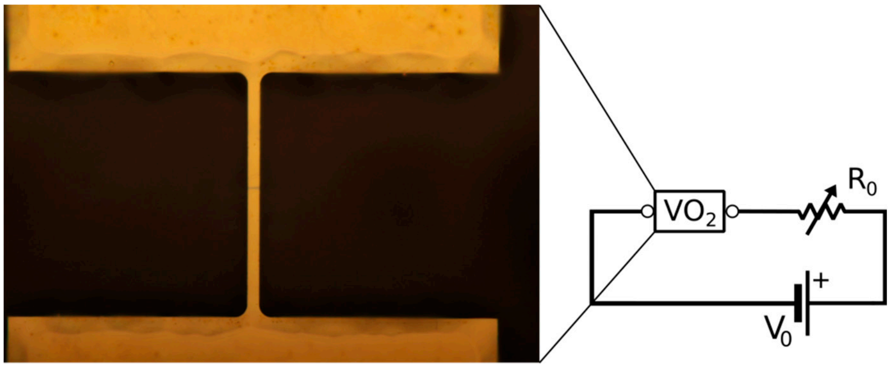
1. Introduction

Typical methods to achieve resonant actuation in micro-electro-mechanical-systems rely on active elements requiring dedicated AC electronic components that increase the total complexity, size and power consumption of the final devices. A different approach consists on using active materials, that can achieve resonant actuation thanks to their intrinsic characteristics such as non-linear electrical response and electro-mechanical couplings. VO_2 is an optimum candidate as active material in micro-/nano-actuators because of its sharp solid state phase transitions (SSPT) at 68 °C that in single crystals can produce strain up to 1% and large applied forces, being at the same time intrinsically fast (ps) [1,2]. Efficient actuation in VO_2 micro-beams or prototypical thin film structures has been already demonstrated [3,4], but the potentialities of this material are still to be further explored, in particular for what concerns its integration in thin film nano-devices. Here, we achieve high-frequency mechanical actuation of micro- and nano-electro-mechanical devices enabling the direct transduction of a DC voltage bias into a mechanical excitation in the MHz range [5]. This result relies on the unique mix of non-linear electrical response and electro-mechanical coupling provided by the concurrent insulator-metal transition and change of crystal symmetry across the VO_2 SSPT, which is employed to realise a spontaneous electrical oscillator capable of exciting selected flexural modes of a free-standing structure.

2. Electrical Oscillations in a VO_2-Based Microbridge

Figure 1a reports a picture of a VO_2-based microbridge, fabricated from a TiO_2(23 nm)/VO_2 (90 nm) crystalline heterostructure by electron-beam lithography followed by selective chemical etching of the substrate. A Ti(5 nm)/Au(45 nm) bilayer was deposited on top of the device to both guarantee low-resistive electrical contacts and localise the voltage bias across the uncovered VO_2 region in the middle of the bridge, which is visible as a lighter strip in Figure 1a. We apply an electrical bias to the microbridge by using the electrical circuit sketched in Figure 1b, where V_0 is a tuneable voltage bias and R_0 a variable resistor. If the current flowing in the VO_2 element is sufficiently high, the temperature increase due to the Joule effect is capable of triggering the SSPT and thus switch the VO_2 element from a high resistive to a low resistive phase [6]. The metal pads limit the spread of the high-temperature phase, which is thus confined in the gap region. This keeps the accumulated stress coming from the SSPT at a small value, resulting in a negligible effect on the mechanical properties of the structure. The current flowing in the VO_2 region produces a local temperature increase due to the dissipated Joule power. The VO_2 phase transition is thus triggered by the electrical current that is determined by the values of R_0 and V_0.



(**a**) (**b**)

Figure 1. Actuation circuit and microbridge device. (**a**) Optical microscope image showing one prototypical microbridge actuated by biasing a VO_2 region (light strip in the middle) with Au gates (yellow areas); (**b**) Schematic diagram of the electrical circuit used to trigger the electrical oscillations in the VO_2. R_0 is a variable resistor and V_0 a tuneable voltage source (1–2 V). See also reference [5].

However, for special combinations of these two parameters an unstable state can be observed, where the VO_2 element continuously switch between the two phases [7]. This is the condition of a typical relaxation oscillator and is a consequence of the non-linear relationship between the state physical variables of the system. One of the most remarkable characteristics of this state is that the frequency of the electrical oscillations can be controlled by tuning the parameters of the circuit, as an example by adding a capacitance or changing the value of R_0. In Figure 2 we show the time plot of the voltage drop across the load resistor R_0 while changing its value with the circuit biased with V_0 = 1.7 V. By changing R_0 form 10 kΩ to 16.25 kΩ the frequency of the electrical oscillations varies with continuity by more than a factor two. The double-exponential waveform is typical of this kind of state and, together with the aforementioned structural changes at the SSPT, is one of the key ingredients that determine the high-frequency mechanical actuation.

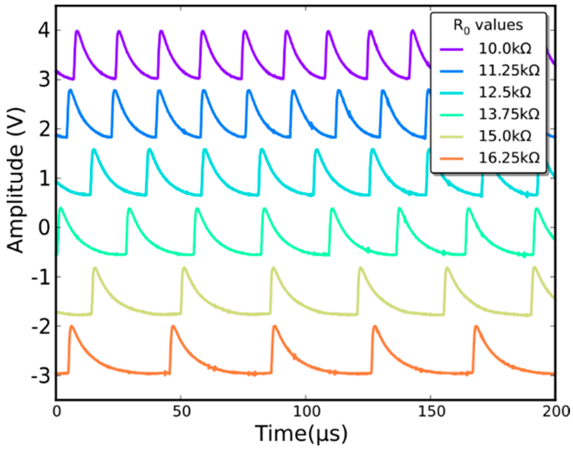
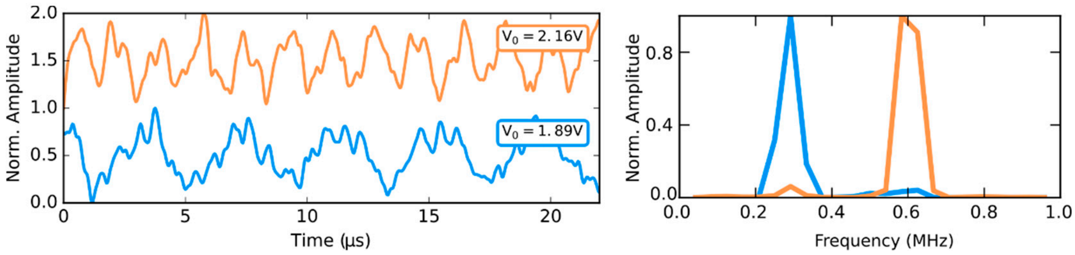


Figure 2. Electrical oscillations induced in the VO_2-based microbridge under a constant voltage bias (1.7 V) for different values of the electrical resistance in series. The chosen value of R_0 determines the frequency of the electrical oscillations and thus the frequency of the electro-mechanical oscillations. Traces represent the voltage across R_0 and are shifted vertically of 1.2 V for better clarity.

3. Spontaneous Mechanical Actuation from DC Bias

As a consequence of the periodic SSPT triggered by the electrical bias, the VO_2 element exerts an oscillating mechanical force on its parent structure. This fact can be employed to obtain resonant excitation by tuning the frequency of the electrical oscillations to match one of the mechanical eigenmodes of the free-standing structure. The power density of the signal reported in Figure 2 is spread across several harmonic components. It is thus possible to obtain resonant mechanical actuation by matching one of these components with the desired mode of the structure. This is demonstrated in Figure 3a,b, showing the time plot and the spectral power density of the mechanical motion of the microbridge measured for two different frequency values of the electrical oscillations. The measurement is performed using an optical lever technique, i.e. by measuring angular deflection with a laser beam focused on the structure. The blue trace is measured with an electrical oscillations frequency of about 50 kHz, whose 7th harmonic component is used to excite the first flexural mode of the structure at 350 kHz. The orange trace corresponds to an electrical oscillation of 60 kHz, whose 10th harmonic components excite the second flexural mode at about 600 kHz. Mode-selective excitation comes from the different spacing between the harmonic components of the electrical oscillations and the flexural modes of the structure, making possible to have the matching condition for one specific mode at a time.



(**a**) (**b**)

Figure 3. Selective excitation of different mechanical modes of a VO_2-based microbridge under DC bias. (**a**) Time plot of the microbridge deflection as measured by an optical lever setup for two different values of V_0. (**b**) Fourier Transform of (**a**) showing the dominant harmonic components of the signal, corresponding to the first (blue) and second (orange) flexural mode of the structure in Figure 1a.

In conclusion, the SSPT of VO_2 was employed to realize a direct conversion from a DC voltage bias to a high frequency mechanical excitation in micro and nanostructures. This actuation scheme will enable the design of novel autonomous devices powered by independent DC sources.

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Conflicts of Interest: The authors declare no conflict of interest.

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