Photothermal actuation of VO$_2$:Cr-coated microcantilevers in air and aqueous media

Emmanuelle Merced$^{1,2}$, Noraica D´avila$^{1,2}$, David Torres$^2$, Rafmag Cabrera$^{1,2}$, Félix E Fernández$^3$ and Nelson Sepúlveda$^{1,2}$

$^1$ Applied Materials Group, Electrical and Computer Engineering Department, Michigan State University, E Lansing, MI 48824, USA
$^2$ Applied Materials Group, Electrical and Computer Engineering Department, University of Puerto Rico-Mayaguez, Mayaguez, PR 00681, USA
$^3$ Applied Materials Group, Physics Department, University of Puerto Rico-Mayaguez, Mayaguez, PR 00681, USA

E-mail: nelsons@egr.msu.edu

Received 18 March 2012, in final form 25 June 2012
Published 3 August 2012
Online at stacks.iop.org/SMS/21/105009

Abstract
A silicon cantilever coated with a Cr-doped vanadium dioxide (VO$_2$) thin film was photothermally actuated with a red pulsed laser in order to study its dynamic performance in air and in water. Very high cantilever vibration amplitudes were obtained in air ($\sim$46.8 $\mu$m) up to 500 Hz, while in water a decrease in amplitude was observed from the starting pulse frequency of 1 Hz with relatively high amplitudes ($\sim$3 dB) up to $\sim$10 Hz. Although fluid drag was found to have no effect on the cantilever response through the measured frequency range in either media, numerical simulations show that heat dissipation through the anchor and the surrounding fluid was the cause of the amplitude reduction observed. These results suggest the use of Cr-doped VO$_2$-coated cantilevers as optically driven actuators with high deflections in liquid media.

(Some figures may appear in colour only in the online journal)

1. Introduction
VO$_2$ has a monoclinic crystalline structure (M$_1$) at room temperature, which changes to a tetragonal, rutile-type (R) structure at a transition temperature ($T_c$), usually close to 68$^\circ$C. With this transition—which is best described as a Mott–Peierls transition—the electrical, optical, and structural properties of the material undergo drastic changes [1–4]. In terms of electrical conductivity, the transition is often referred to as insulator-to-metal (IMT) or metal-to-insulator (MIT)—there is no uniform convention—either choice being equally valid, since the transition is reversible. Defects in the VO$_2$ lattice may generate room-temperature phases different than the typical monoclinic M$_1$ phase of pure VO$_2$, which has an influence on the magnitude of the changes of the materials’ properties and on $T_c$. Such defects can be induced through substitutional vanadium ions (V$^{5+}$ for V$^{4+}$), or via doping by Cr, Ti, W, Fe, among other elements [5–8]. Cr-doped VO$_2$ crystals show a $T_c$ value slightly higher than undoped VO$_2$, and a more abrupt change in electric properties that decreases with Cr concentration [7]. The structural changes in VO$_2$ during the phase transition have been used recently to cause large deflections of micro- and nanometer-sized structures [9, 10]. It has been also found that single crystal silicon (SCS) microcantilevers coated with VO$_2$ thin films doped with Cr in concentrations of $\sim$2.4 at.%—in which case the room-temperature structural phase is not M$_1$ but a different monoclinic phase (denoted M$_2$)—show larger curvature changes across the IMT than those coated with undoped VO$_2$ film [11].

The use of photothermal excitation of microcantilevers is gaining importance in atomic force microscopy (AFM) applications where the structures are operated in liquids, such as in Bio-AFM [12, 13]. This type of excitation provides a noninvasive wireless method for controlling the bending mechanism. Hence, the very large bending amplitudes demonstrated in microcantilevers coated with VO$_2$ and Cr-doped VO$_2$ thin films are of interest in this...
regard. Photothermally driven VO$_2$-coated Si cantilevers actuated in air only were in fact recently demonstrated, and a detailed discussion of the observed behavior was presented [14]. This paper extends that previous work by providing a complete discussion on the performance of SCS microcantilevers coated with Cr-doped VO$_2$ thin films when actuated photothermally in water, revealing the potential use of these types of microactuators for bio-applications. The performances of the microcantilever in both media are extensively compared using the higher curvature changes obtained with the VO$_2$:Cr film. All measurements performed in this work were done in micrometers, as opposed to the previous work where only relative displacement values were studied. Photothermal actuation was achieved in both media by modulating a laser diode with a square wave and focusing it at the cantilever plane in order to conduct two types of studies: (1) frequency response experiments, where the amplitude of oscillation of the cantilever was measured as a function of excitation frequency and (2) time response experiments, where the tip displacement of the cantilever was monitored as a function of time through a complete cycle of the modulated laser.

2. Experimental procedures

2.1. VO$_2$ deposition and characterization

Cr-doped VO$_2$ thin films were deposited on a chip including a 250 µm long, 35 µm wide, and 1 µm thick SCS cantilever. The conditions for film growth were very similar to those reported previously [11]. Briefly, VO$_2$:Cr-doped (V$_{1-x}$Cr$_x$O$_2$) films were deposited by pulsed laser deposition (PLD) using a KrF excimer laser (Lambda Physik Compex 110 laser, wavelength $\lambda = 248$ nm, 20 ns pulse duration, 10 pulses $s^{-1}$ repetition rate, $\sim 2.0$ J cm$^{-2}$ fluence at the target), and a mixed-compound rotating target fabricated by cold-pressing micronized V$_2$O$_5$ and Cr$_2$O$_3$ powders in desired proportions. The deposition was performed in a mixed Ar and O$_2$ atmosphere (10 sccm and 15 sccm gas flows, respectively) at a total pressure of 25 mTorr. The SCS cantilever chip was attached with silver paste to a SiO$_2$ substrate, which in turn was attached to a resistive heater. The film was grown at a substrate temperature of 550°C.

After deposition, film thickness was determined to be $\sim 160$ nm using a Tencor Alphastep profilometer scanning over a film step created on the substrate. Film structural characterization was done by x-ray diffraction (XRD), using Cu Kα radiation in a Bruker D8 Discover diffractometer. The XRD study, performed on the glass substrate on which the cantilever chip was attached during film growth, verified that the room-temperature phase of the deposited VO$_2$:Cr film was in fact M$_2$. To extend film characterization, film resistance was measured as a function of temperature across the IMT. The result, shown in figure 1, demonstrates a change of more than two orders of magnitude, which is similar to previous results for good quality polycrystalline VO$_2$ films grown on glass or SCS. The transition temperature is lower than for M$_1$-phase VO$_2$ by several degrees, which is contrary to what is known to occur for bulk crystals with a similar composition [7, 15]. The difference may be related to the high tensile stress which develops in the film. As expected, the Cr-doped VO$_2$ transition resistance drop is higher than previous results for undoped VO$_2$ films [16].

2.2. Conductive heating actuation: static experiments

Cantilever tip deflection was measured directly using a microscope equipped with a filar eyepiece (Lasico, model 1602E-10). These measurements were performed from 30 to 100°C in temperature steps of 2°C for a complete heating–cooling cycle. The maximum displacement of the cantilever tip ($\Delta x$) was measured to be $\sim 73$ µm, corresponding to a minimum value of the radius of curvature ($R_c$) (calculated using $\Delta x = 2R_c\sin^2(\frac{\alpha}{2})$) of 2400 m$^{-1}$ (see figure 2(a)). The observed curvature change is mainly due to the material’s IMT: as the material is heated and reaches the transition temperature, the crystal plane parallel to the substrate contracts, producing a tensile stress that bends the cantilever upwards [9–11, 14]. For deposited thin films, this transition is fully reversible and is known to occur in femtoseconds [4]. For the cantilever in air, the sample temperature was maintained by a heater to which the chip was attached, monitored with a thermocouple and controlled in a closed-loop configuration (see figure 3(a)). Figure 2(b) shows superimposed images of the coated cantilever at room (30°C) and high temperatures (90°C). The displacement value shown in the inset was estimated using the cantilever length (250 µm) as a reference, and is nearly the same as the maximum value obtained from the direct measurements with the filar eyepiece at the same temperatures. A similar experiment was conducted with the cantilever chip immersed in a small (~2 cm$^3$ volume) in-house built water tank filled with deionized (DI) water. The cantilever was cemented with a high thermal conductivity paste to the inside surface of the water tank bottom which was fabricated from an aluminum disk with $\sim 1$ mm thickness.
Figure 2. Cantilever tip deflection as a function of temperature measured optically in air (a). Superimposed side views of the two actuation limits in air (b) and water (c). The total tip deflection change for the cantilever from 30 °C (horizontal cantilever) to 90 °C (bent cantilever) in both media is 68 µm.

Figure 3. Measurement setup for frequency and time response experiments (a) and optical setup for the side-view images of the microcantilever (b).

The tank bottom was also cemented to a Peltier heater. The temperature of the water tank was controlled as before, but the water temperature was also measured directly with a second thermocouple. It was verified that, at equilibrium, this did not deviate by more than 1 °C from that of the heater surface. The water temperature was increased until maximum cantilever tip deflection was observed. From superimposed pictures (figure 2(c)), the maximum cantilever tip deflection in water was found to be, as expected, essentially the same as previously observed in air.
2.3. Photothermal actuation: dynamic experiments

The following two types of experiments were designed to study and compare the dynamics of photothermally driven VO₂:Cr-coated microcantilevers when actuated in air or water. The setup schematically shown in figure 3(a) was used, with the tank empty or filled with DI water, according to the case. In the frequency response experiments, a modulated driving laser (672 nm wavelength) was focused on the cantilever plane, illuminating the film surface, while the maximum amplitude of the tip oscillation was monitored as a function of frequency using a side-looking CCD camera. In the time response experiments the transient signal of the tip displacement as the cantilever was illuminated by a heating pulse was recorded by detecting the beam from a second laser (low power, 808 nm wavelength), which was reflected from the cantilever tip.

The chip body and tank base, cemented to the heater, acted as a heat sink. For experiments in air, this heat sink was kept at room temperature (~25 °C). As a result of the much higher cooling efficiency of water in comparison to air, it was found convenient for the experiments in water to bring the initial temperature to 45 °C, which is closer to the IMT region, using the heater. With this arrangement, the power of the actuating laser beam used in each case was 100 mW and 150 mW in air and in water, respectively. These values were chosen based on preliminary experiments, in which the minimum power required to cause maximum cantilever deflection was empirically obtained. Both the driving and tip deflection measuring laser beams entered from the top, so that there was no interaction with tank walls. Some of the laser power (~2%) is reflected at the air–water interface. Since the absorption coefficient of water (εwater) is approximately 0.4 m⁻¹ at λ = 672 nm, and the distance traveled by the beam in water was ~1 cm or less, light absorption losses are less than 1%. Hence, the laser beam pulses cause negligible heating of the water in the tank. A top-looking charged-coupled device (CCD) camera and video monitor were used as a visual aid in order to correctly position both laser beams on the cantilever. A 30% transmittance neutral density filter (NDF) was placed before the CCD, which was sufficient to see the cantilever and laser spot without saturating the CCD. The driving laser was focused on the cantilever plane with a spot size diameter corresponding to that of the microcantilever’s length (~250 μm), so that it was fully illuminated. The laser output was modulated as a square wave with 50% duty cycle using a house-built electronic circuit. The ‘on’ value corresponded to the minimum power required for maximum bending for the cantilever (for each medium). Average irradiance during the ‘on’ half-cycle was ~1.3 kW cm⁻² (in air) and ~1.9 kW cm⁻² (in water). The sensing laser used for the time response experiments was operated continuously and was focused on the tip of the cantilever with a laser spot size close to the width of the cantilever (~40 μm). Its intensity was kept to the minimum required for detection, so it would not contribute significantly to cantilever heating. The reflected sensing beam was detected by a linear position sensitive diode (PSD) (Hamamatsu C-3683-1) with very high sensitivity in the near IR range. The PSD was covered with a low-pass optical filter in order to block light from the red driving laser and reduce noise. The PSD outputs a voltage proportional to the position of the laser spot, which was observed and recorded in a storage oscilloscope. Since the output of the PSD represents a relative displacement, the system was calibrated using the side-looking CCD camera. This camera and its corresponding optical components—shown in figure 3(b)—were arranged in a spatial plane perpendicular to the first setup, providing a side view of the cantilever. For illumination, a white light source was aimed onto the sample through a long working-distance objective lens. The reflected light was imaged by the same lens onto the CCD camera after separation from the input light by means of a beam splitter (BS). The resulting image was a sharp amplified view of the cantilever side. By using pixel rulers, the deflection was measured and used to calibrate the output signal of the PSD (see figure 2). The CCD refresh rate was ~30 Hz, which means that video images can follow cantilever motion only at the lower range of driving frequencies explored, but the extrema of the oscillations can still be clearly observed. The magnitude of cantilever tip oscillation amplitudes was obtained from superimposed images of these extrema as the frequency of the driving laser was increased.

3. Results and discussion

3.1. Frequency response experiment

The results for the frequency response experiments in both fluids are shown in figure 4. Figure 4(a) shows the cantilever tip amplitude (in micrometers) as a function of actuation frequency in air (dotted line) and in water (solid line), while figure 4(b) shows the same results with the amplitude expressed in decibels (dB), relative to the amplitude at 1 Hz, as a function of frequency in a log scale (i.e. a Bode diagram). For illustrative purposes, figure 5 shows still images from the video taken with the side-view camera as the cantilever was actuated with the pulsed laser in air or in water, and at two different driving frequencies.

With the cantilever in air, the vibration amplitude is constant (~47 μm) up to a frequency of ~500 Hz, when it starts decaying and reaches the 3 dB loss (~33 μm amplitude) at ~1 kHz and afterwards continues decaying at a rate of ~22 dB/decade. These results obtained with the cantilever in air are similar to those presented in previous work, although the experimental conditions, including cantilever length, coating composition and thickness, are different [14]. For the case where the cantilever is submerged in water, the initial oscillation amplitude is ~53 μm. From 1 Hz up until ~7 Hz, the amplitude decays at approximately ~1.5 dB/decade, where it reaches ~1.3 dB (~45.5 μm). From ~7 Hz, the amplitude starts decaying at a much more rapid rate of approximately ~8.5 dB/decade and reaching a 3 dB loss (38 μm), compared to its initial gain, at approximately 11 Hz. After ~30 Hz, the decay rate becomes slightly steeper as the frequency is increased, up to the
Figure 4. Vibrational amplitude in micrometers (a) and decibels (b) as a function of laser pulse frequency for the cantilever actuated in air and water.

maximum measured frequency of 200 Hz. The amplitude, after this driving frequency, was too small to be measured by the means employed. This strong amplitude reduction in water is illustrated in figure 5. At a driving frequency of 100 Hz, the cantilever in air still vibrates at maximum amplitude, while in water it has already decayed from ~53 to ~11 µm. At 1 kHz, there is no longer an observable response in water, while it is still ~33 µm in air. In order to test for response degradation under repeated laser pulses with the beam intensities used for actuation during the experiments in both media, the cantilever was exposed, for 2 h, to laser pulses of 100 Hz and 10 Hz in air and in water, respectively. After these exposures the cantilever had been subjected to tens of thousands of pulses and showed no reduction in vibration amplitude.

The total deflection amplitudes at very low frequencies for the photothermally driven cantilever, shown in figure 4(a) for both media, are less than the maximum deflection achieved when actuated with the heater alone—see figures 2(b) and (c). Furthermore, the low-frequency amplitude of the laser-actuated cantilever is larger in water than in air. These features are considered next.

In the conductive heating actuation experiments (i.e., with the heater only), the temperature distribution of the complete chip (including the cantilever and its anchor) is essentially uniform at each temperature level. Hence, for post-transition temperatures measured at the substrate it can be assumed that the phase transition should have occurred for all of the VO$_2$:Cr film. In contrast, during photothermal actuation, heat is evolved only at the cantilever itself, while the chip body acts as a heat sink which essentially remains at the initial temperature. Hence, temperature gradients are produced along the cantilever and, as shown below, a zone near the anchor never reaches a temperature high enough to complete the IMT. During the photothermal driving experiments with the cantilever immersed in water the initial system temperature was 45°C, which suggests that, upon illumination, a larger portion of the cantilever should have reached high enough temperatures for the film material to undergo the IMT. Therefore, it is reasonable that maximum tip displacement would be lower during photothermal actuation than during the conductive heating tests, and that tip displacement amplitude at very low frequencies would be greater for the water-immersed cantilever than for the cantilever in air.

A numerical simulation using the finite element method (FEM), implemented with COMSOL software, was conducted in order to verify these ideas, and the results are summarized in figure 6 [17]. This study consisted of a steady-state heat transfer analysis of the simulated geometry. The computational model used a two-dimensional cross-sectional geometry of the VO$_2$:Cr-coated Si cantilever with all of its dimensions corresponding to that of the cantilever in question, and including the anchor, which was considered as a heat sink. The heat produced by the laser was simulated by an inflow heat flux boundary in the top cantilever face with a length and width corresponding to that of the cantilever (250 µm and 35 µm, respectively). The heat flux absorbed by the cantilever in each case was estimated from the light intensity values used in the experiments (100 mW for air and 150 mW for water) and relevant optical properties of the materials. At a wavelength of 672 nm, a VO$_2$ film will reflect ~23% of the light and absorb ~60% of the light not reflected [14]. The optical properties for VO$_2$:Cr at the relatively low Cr concentrations used were assumed not to deviate significantly from those of pure VO$_2$. Assuming, for simplicity, no loss of laser intensity in air or water and neglecting light absorption in the silicon substrate, which is much lower than for VO$_2$, the total values of heat flux used for the simulations of the structure in air and in water were 94.2 W cm$^{-2}$ and 141.1 W cm$^{-2}$, respectively. To take into account the surrounding air and water media, the cantilever was drawn in an enclosure that simulated these through their respective thermal properties. The initial conditions for the temperature were set to 25°C in air and 45°C in water. The thermal properties assumed for all materials are summarized in table 1. Commonly known values for Si, water and air were used, and VO$_2$ properties were taken from the literature [18–21]. Although driving laser pulses
Figure 5. Still images from the video taken with the side-view CCD camera as the cantilever was actuated at the indicated frequencies with the heating laser in air (top images) and in water (bottom images). The measured vibrational amplitude is shown for each case. After 200 Hz there was no measurable displacement for the cantilever in water.

Table 1. Materials’ properties (at room temperature) used in the finite element simulations and for discussions of results.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density $\rho$ (kg m$^{-3}$)</th>
<th>Thermal conductivity $\kappa$ (W m$^{-1}$ K$^{-1}$)</th>
<th>Heat capacity at constant pressure $C_p$ (J kg$^{-1}$ K$^{-1}$)</th>
<th>Young’s modulus $E$ (GPa)</th>
<th>Dynamic viscosity $\eta$ (Pa s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VO$_2$</td>
<td>4340</td>
<td>5</td>
<td>678</td>
<td>140</td>
<td>—</td>
</tr>
<tr>
<td>Si</td>
<td>2329</td>
<td>148</td>
<td>700</td>
<td>170</td>
<td>—</td>
</tr>
<tr>
<td>Air</td>
<td>1.18</td>
<td>0.025</td>
<td>1005</td>
<td>—</td>
<td>1.98 x 10$^{-5}$</td>
</tr>
<tr>
<td>Water</td>
<td>997.05</td>
<td>0.6</td>
<td>4180</td>
<td>—</td>
<td>8.9 x 10$^{-4}$</td>
</tr>
</tbody>
</table>

with larger intensities would have caused larger temperatures near the anchor and ideally shown the same cantilever tip displacement for both actuation methods, such intensities would have likely damaged the VO$_2$:Cr film. As shown by the FEM results in figure 6, even with the intensities used, the maximum temperature near the cantilever tip can reach values much higher than required to complete the transition, while a zone near the anchor can remain at temperatures under the IMT region. This effect of overheating near the tip is less pronounced for the cantilever in water because of its higher cooling efficiency. Nevertheless, even in that case the model indicates that the region near the tip would have reached temperatures of $\sim$140°C. In water, a larger fraction of the cantilever length reaches temperatures above the IMT, compared to the case in air. Thus, larger bending can be obtained in the former case. This justifies the experimentally observed difference in maximum bending in the two media during photothermal excitation.

The effect of drag by the surrounding medium is now studied. In [14] this was considered for the cantilever in air and was found to be negligible for the operating frequency range. A similar approach is taken here to include the case of water as the surrounding medium. When viscous forces are important the vibrating cantilever can be modeled as a sphere of radius $R_s$ calculated according to the method presented by Lamb [22]. For the cantilever in question we approximate $R_s = 50 \mu$m. For the range of vibration frequencies of interest

Figure 6. Calculated model results for temperature as a function of distance from the anchor of the cantilever in both media during steady-state conditions of the laser pulse. These results were obtained from steady-state analysis of the photothermally actuated cantilever.
here the value of Reynolds’ number satisfies \( Re \ll 1 \) for the lowest frequencies, but for the higher frequencies \( Re \sim 1 \) in either medium. Hence, while only viscous drag is relevant at low frequencies, inertial effects cannot be neglected at the higher frequencies (\( \sim 1 \) kHz in air, \( \sim 100 \) Hz in water). For a sphere oscillating in a fluid, the drag exerted by the fluid can be approximated as:

\[
F_d = 6\pi \rho \eta \left( 1 + \frac{R_s}{2\eta} \right) \dot{x} + \frac{2}{3} \pi \rho R_s^3 \left( 1 + \frac{9}{2\rho} \frac{\eta}{\rho \omega} \right) \ddot{x},
\]

where \( \eta \) and \( \rho \) are the dynamic viscosity and the density of the medium, respectively, \( \omega \) is the angular frequency of vibration and \( x \) and \( \dot{x} \) are the sphere’s velocity and acceleration, respectively [23]. The general differential equation for cantilever vibrations with a harmonic driving force \( F_h(\omega) \) is given by

\[
\left( m_{eff} + \beta_2 \dot{x} + \beta_1 \dot{x} + k_{eff} x \right) = F_h,
\]

where \( \beta_1 \) and \( \beta_2 \) are the velocity and acceleration components of the drag from equation (1), \( m_{eff} \) is the effective mass of the cantilever, defined as \( m_{eff} = \frac{11}{12} m \), where \( m \) is the actual cantilever mass, and \( k_{eff} \) is the effective cantilever spring constant for the bimorph cantilever [24, 25]. The amplitude of vibration as a function of frequency for the harmonically driven cantilever can be written as:

\[
A(\omega) = \frac{F_{ho}}{\sqrt{\left( \frac{k_{eff} - \omega^2}{m_{eff} + \beta_2^2} \right)^2 + \left( \frac{\dot{x}_{eff}}{m_{eff} + \beta_2^2} \right)^2}}
\]

where \( F_{ho} \) corresponds to the arbitrary amplitude of force \( F_h(\omega) \). Figure 7 shows the theoretical frequency response of the cantilever in air and in water obtained from equation (3) with the materials’ property values listed in table 1. Although these calculated results are obtained from a very simplified model, it may be seen that the quality factor for the case of water is smaller than the case of air (the resonant peak is wider in water than in air) as can be expected [26]. These results only include the effect of air or water drag on cantilever amplitude. Any damping due to internal losses in the cantilever is ignored. It is noted that there is a significant pull-down of the resonant frequency, particularly for vibrations in water, but effects on the driven motion due to drag occur at much higher frequencies than the ranges measured experimentally in each case. Thus, it is concluded that the amplitude decay observed in the measurements is essentially unrelated to fluid drag and can instead be a consequence of heat transfer effects in the cantilever and the surrounding medium.

### 3.2. Time response experiments

To better understand the effect of air and water surrounding the pulse-driven cantilever, the time response experiments were performed. Figures 8(a) and (b) shows the measured tip displacement as a function of time for the cantilever in air and in water. In both cases the laser was turned on and off at the specified ‘laser on’ and ‘laser off’ instants. A slower response is observed for the cantilever in water, in which case the rise-time is \( \sim 30 \) ms, compared to \( \sim 0.58 \) ms in air and the fall-time is \( \sim 32.5 \) ms, while in air it is just \( \sim 0.45 \) ms. Both, rise- and fall-times are defined here as the time it takes the cantilever to go from 10% to 90% of its final deflection value. The relatively fast rise- and fall-times for the cantilever in air are in good agreement with the observed 3 dB cut-off frequency of nearly 1 kHz. While the frequency dependence results for the cantilever in water were more complex, the 3 dB cut-off frequency, at slightly more than 10 Hz, is also in agreement with the observed transient times. The transient response in air shows small oscillations just after the laser pulse is turned on and just after it is turned off (figure 8(a)). The same type of effect was observed before for a similar case [14]. These oscillations may be caused by rapid thermal transients along the cantilever associated with the fact that light intensity is not constant across the incident beam. These oscillations were not observed in the case of the cantilever immersed in water. It is possible that the enhanced heat conduction provided by the water in contact with the cantilever reduces the magnitude of these transients.

Further analysis of the transients in the cantilever was performed by a heat transfer transient analysis, implemented in COMSOL, with the same geometry and materials parameters used before through a period of the simulated heating pulse while the tip temperature was monitored as a function of time. Figures 9(a) and (b) present the results obtained for both cases. Although the simulation did not include any mechanical response, and therefore neglected changes in irradiance caused by changes in cantilever inclination through the transition, the dynamic performance of the cantilever in each media can be qualitatively and quantitatively explained by these temperature transients. The heating and cooling transient times in air occur in milliseconds (\( \sim 0.85 \) ms) while in water these last almost two orders of magnitude longer.
magnitude more (~70 ms). It is noted that the calculated fall-time and rise-time are somewhat different due to the asymmetric heating conditions in the simulation. Thus, the simulated cantilever thermal dynamics yield transient times that are just a factor of two larger than the experimental measurements. Considering the simplicity of the model assumed, these results are very reasonable and strongly support the idea that the mechanism limiting the vibrational amplitudes of the cantilever is heat transfer from the cantilever through the anchor and the surrounding media.

One additional simulation was performed where the cantilever geometry, immersed in both media, was scaled down by one order of magnitude in order to study the effect on tip temperature transients. Since Reynolds’ number for vibrating objects is proportional to frequency and to the square of the object’s size, these assumptions imply that the viscous regime will extend then to much higher frequencies and inertial fluid forces will be less important. Table 2 shows the simulation results where a cantilever with length and thickness one order of magnitude less than the cantilever used in this experiment was simulated in both media. For comparison, the rise-times obtained for the actual cantilever geometry are also included in table 2. The VO$_2$ film thickness was kept at 160 nm for all simulations. The results show that heat transfer transient times are reduced by over one order of magnitude, which implies that photothermal actuation of cantilevers with much smaller dimensions can produce high curvature oscillations in air and in water up to much higher frequencies than those observed in the experiments reported here. Photothermal actuation can be implemented in other fluids, as long as the light wavelength used to drive the device can be absorbed by the VO$_2$ and is not significantly absorbed by the surrounding fluid.

4. Conclusion

The dynamics of a VO$_2$:Cr-coated microcantilever have been studied in air and in water using results from frequency and time response experiments. These revealed that very high deflections can be obtained through pulsed laser excitation in both media although for the cantilever in water these deflections are hampered by the higher thermal conductivity. Actuation with large amplitudes in aqueous media suggests
promising biological and biomedical applications. Through the use of finite element analysis simulations, heat transfer to the anchor and, particularly in the case of water, the surrounding medium was found to be the dominant mechanism that limits upper cantilever actuation frequency. Meanwhile, it was argued that fluid drag has no effect in the response through the frequency range studied. It is expected that higher frequency operation with large curvature changes for this type of device, as well as for other light-driven micro-electromechanical systems based on the same actuation mechanism that limits upper cantilever actuation frequency.

### Acknowledgments

Nelson Sepúlveda is supported by the National Science Foundation under Grant No. ECCS-1139773 (NSF-CAREER Program). Emmanuelle Merced is supported by the National Science Foundation under Grant No. DGE-0802267 (Graduate Research Fellowships Program).

### References

1. Qazilbash M M et al 2007 Mott transition in VO$_2$ revealed by infrared spectroscopy and nano-imaging Science 318 1750–3
17. Heat Transfer Module, COMSOL Multiphysics Version 4.2 Stockholm

Table 2. Calculated rise-times for the heat transfer simulation, in both media, for a cantilever with the geometry used in this experiment and for a cantilever with a scale size reduced by a factor of 10. $L$ and $t$ are the length and thickness of the Si cantilever, respectively.

<table>
<thead>
<tr>
<th>Media</th>
<th>Cantilever dimensions ($\mu$m)</th>
<th>Simulation rise-times (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>$L = 250$ $t = 1$</td>
<td>$8.5 \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td>$L = 25$ $t = 0.1$</td>
<td>$3.0 \times 10^{-5}$</td>
</tr>
<tr>
<td>Water</td>
<td>$L = 250$ $t = 1$</td>
<td>$7.0 \times 10^{-2}$</td>
</tr>
<tr>
<td></td>
<td>$L = 25$ $t = 0.1$</td>
<td>$5.5 \times 10^{-3}$</td>
</tr>
</tbody>
</table>