Electrical oscillation generation with current-induced resistivity switching in VO$_2$ micro-channel devices

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ABSTRACT

We report large amplitude modulation waveforms as large as ~ 10 V using vanadium dioxide micro-channel devices operating under current-controlled conditions. The self-sustained electrical oscillations were generated by controlling the applied current in the negative differential resistance region of the investigated devices. An appropriate value of internal capacitance was achieved as parasitic capacitance in the device structure to stabilize the electrical oscillations. This eliminates the need of an external pulsed source or any external passive component connected to the micro-channel devices. Amplitude and frequency of the oscillation were tuned by illuminating the device micro-channel with an external laser. An equivalent circuit model was developed to simulate the waveforms. A good agreement between experiment and simulation was verified.

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1. Introduction

Novel electronic switches, memristive systems and oscillators are critical components for a variety of tunable electronics applications. Transition metal oxides are promising candidates in realizing such devices. Among the various transitional metal oxides, stoichiometric vanadium dioxide (VO$_2$) is receiving considerable attention due to its marked and reversible insulator-to-metal phase transition (IMT) [1]. Pronounced changes in electro-optical properties across the IMT is a signature of this process. Below the IMT temperature, VO$_2$ exhibits a monoclinic crystal structure [2,3] with $a \sim 0.7$ eV energy band-
gap [4,5] and high electrical resistivity (the insulator state). In contrast, beyond the phase transition, VO$_2$ exhibits a rutile structure, with no band-gap and very high electrical conductivity (the metallic state) [2,3]. The IMT in VO$_2$ can be triggered by the application of an external electric field, heat or an optical excitation. Such tunable capability can be exploited for designing microelectronic and optoelectronic devices beyond CMOS technology with reconfigurable characteristics [6]. VO$_2$-based terahertz modulators [7,8], analogue modulators [9], tunable meta-materials [10,11], field-effect transistors [12–14] and memristors [15,16] have been already demonstrated.

Two-terminal electrical devices incorporating VO$_2$ micro-channels are of particular interest due to their spontaneous electrical oscillation characteristics [17–21]. These devices exhibit well-pronounced negative differential resistance (NDR) [17,18], an essential attribute for practical realization of electrical oscillators. Such oscillators do not require inductive components to generate the waveforms. This can be potentially used to fabricate tunable micro- or nano-oscillators for a variety of applications spanning from analogue electronics to artificial neural networks [19].

Under specific biasing conditions, the two-terminal device resistance spontaneously oscillates between the insulating and the metallic states. The dynamics of the phase transition in two-terminal VO$_2$ devices is different under voltage controlled (VC) or current controlled (CC) modes of operation [22,23]. The VC phase transition exhibits a much larger hysteresis loop width when compared to the CC mode of operation. Also, under CC operation conditions less Joule heating is generated making this mode of operation more attractive than the VC one [17,24].

VO$_2$ oscillators, excited by voltage actuation [18,25] or current actuation [24] have been reported. However, the generation of electrical oscillations with such devices requires an external current or voltage pulse source and an external resistive component connected to the device. Voltage actuation with a DC voltage still requires an external resistive component to generate the oscillations [17]. A combination of an external resistor in parallel with a capacitor is required in the relaxation oscillation experiments [26]. In this work, we show that electrical oscillations under current actuation in VO$_2$ two-terminal devices can be achieved using only the internal capacitance of the investigated devices, thus eliminating the need of an external current pulse source or any passive external electrical component. We demonstrate very stable oscillation waveforms for over millions of cycles without any significant performance degradation. This reduction in the complexity of the oscillator circuit is significant for prospective large-scale integration and fabrication of micro- or nano-oscillators in a single chip. In order to validate our experimental results, we developed an equivalent circuit model and compared the simulated results with measured self-oscillation. We have also investigated the effects of the optical power excitation from an external laser illuminating the device micro-channels on the frequency and amplitude of the oscillations.

2. Experiments

Planar VO$_2$ micro-channel devices investigated here were fabricated using conventional photolithography, plasma etching, electron-beam metal deposition and lift-off techniques. First VO$_2$ films ~ 130 nm thick were deposited on c-plane (0001) oriented sapphire substrates using the reactive DC magnetron sputtering technique [27]. Then the VO$_2$ films were patterned into long straight line-shapes (~ 400–500 µm length) with 10 µm or 20 µm in width by plasma etching following the first lithography step. Next, a second lithography step was performed followed by the deposition of 100/20-nm-thick Au/Ti layers using the electron-beam deposition technique. Finally, the electrodes were defined using a lift-off procedure in acetone. Figure 1(a) shows a representative optical microscope image of a VO$_2$ device with 20-µm channel length ($L_C$) and 20-µm channel width ($W_C$). The device design layout is similar to that previously reported by Sakai et al. [17,28]. The width of the electrodes was designed to be much larger than the width of VO$_2$ lines to provide a uniform electric field across the channel region and to prevent any delayed phase transition outside of the electrode region [17,18].

After sample fabrication, the entire chip was housed inside a ceramic package and wire-bonded in order to perform the electrical characterization experiments. The package was then placed over a thermoelectric heater/cooler controlled stage for varying the temperature ($T$). A computer-controlled DC power source was used to provide power and to monitor the current and the voltage across the devices. A 0–5 kΩ potentiometer was used as an external load resistor ($R_{eq}$). A digital oscilloscope was used for recording the electrical oscillation waveforms. Two adjacent electrodes were used in our experiments. The change in resistivity during the IMT is depicted in Figure 1(b) for increasing and decreasing temperatures ($T$). Such measurements were performed for a VO$_2$ thin film grown under similar conditions. Since the VO$_2$ micro-channels used in our experiments exhibited a relatively high resistance at room temperature (~ 150 kΩ), all the experiments were performed at stage temperatures in the range 50 < $T_s$ < 65 °C, which is still lower than the VO$_2$ phase transition temperature [9], during CC or VC mode of operation. This procedure was used to reduce the switching threshold voltage to achieve the
IMT, preventing electrical breakdown of the devices. Similar experiments can be performed at room temperature using low resistivity VO$_{2}$ material [17,18]. Measured phase transition temperatures of 342 K and 352 K (see Figure 1(b)) were determined for heating and cooling cycles, respectively. However, there is a ~10 °C temperature offset in $T_S$ where $T_S < T$ due to the thermal impedance of the ceramic package and the heating stage. The total current ($I_{SP}$) in the circuit and the voltage drop ($V_{channel}$) in the micro-channel devices can be simply determined using Ohms’ law relations:

$$I_{SP} = \frac{V_{SP}}{R_{ext} + R_{channel}}$$  \hspace{1cm} (1)

$$V_{channel} = \frac{I_{SP} R_{channel}}{R_{ext} + R_{channel}} = \frac{V_{SP}}{R_{channel}} \left(\frac{R_{channel}}{R_{ext} + R_{channel}}\right)$$  \hspace{1cm} (2)

where $R_{channel}$ is the device resistance, which is essentially the resistance of the VO$_{2}$ channel, and $V_{SP}$ is the voltage supplied by the DC power source. The $R_{channel}$ of each device was measured using a digital ohmmeter at different device temperatures.

The oscillation waveform frequency and amplitude can be varied using an external laser illuminating the devices. We have used a fibre-coupled continuous-wave 980 nm wavelength semiconductor laser diode as the optical excitation source operating at different power levels ($P_o$). The laser output from the multimode optical fibre was placed near the top of the VO$_{2}$ micro-channel region of the devices with a ~300 μm beam diameter.

3. Results

3.1 $I$–$V$ characteristics and electrical oscillations

The current-voltage ($I$–$V$) curves of a 10 µm × 10 µm device (denoted as D$_{10}$) and a 20 µm × 20 µm device (denoted as D$_{20}$) in the VC mode of operation are shown in Figure 2 (a) and (b), respectively. The results shown in Figure 2 were obtained with fixed external resistor $R_{ext} = 4.0 \, k\Omega$ and $T_S = 64$ °C. The $I$–$V$ curves were acquired by applying an increasing or decreasing voltage (or

![Figure 1. Optical microscope image of a D$_{20}$ VO$_{2}$ micro-channel device. (b) The change in VO$_{2}$ resistivity for increasing and decreasing temperatures.](image1)

![Figure 2. $I$–$V$ curves for devices D$_{10}$ (a) and D$_{20}$ (b) under VC mode of operation at increasing (▲) or decreasing (▲) device voltage. The insets show the corresponding $I$–$V$ curves at increasing or decreasing total voltage in the circuit. Measurements were performed with fixed $R_{ext} = 4.0 \, k\Omega$ and $T_S = 64$ °C for both devices. Points $V_{th1}$ and $V_{th2}$ are the threshold voltages corresponding to the forward and the reverse IMT, respectively.](image2)
The external resistor was used to prevent an electrical breakdown when the micro-channel device was in the highly conductive state. The insets in Figure 2 show the corresponding $I$–$V$ curves for the total voltage drop in the circuit. Initially, the channel is in the insulating state with very high resistance. When the device voltage reaches the forward threshold voltage ($V_{th1}$), the IMT occurs and the device current increases. The NDR region is clearly visible after $V_{th1}$ is reached for both devices. Such anomalous behaviour is due to the increase in channel conductivity and simultaneous decrease in the voltage drop across the channel. The higher IMT threshold voltage and larger width of the NDR region in the device $D_20$, when compared to the device $D_{10}$, is attributed to differences in the VO$_2$ channel dimensions. The IMT threshold voltage is higher for larger separation between the two electrodes and it is lower for wider channels. When the VO$_2$ transforms into the metallic state the voltage drop in the channel does not increase significantly with further increase in the current due to its low resistance ($\sim 400 \ \Omega$). The reverse IMT process occurs when the voltage is decreased. The backward threshold voltage ($V_{th2}$) is lower than $V_{th1}$ but similar NDR behaviour can be observed for both devices. The $I$–$V$ curves for the total voltage drop in the circuit exhibits well-defined switching characteristics (see the insets in Figure 2) during the IMT and clear contrast between the metallic and insulating states is observed accompanied by large hysteresis loop widths for both devices. The device $I$–$V$ curves under CC mode of operation are shown in Figure 3 (a) and (b) for the same devices $D_{10}$ and $D_{20}$, respectively. In the VC mode of operation, the voltage is continuously increased (or decreased) while the current is determined by the applied voltage in the device. In contrast, in the CC mode of operation, the current is increased (or decreased) continuously and the voltage drop in the device depends on the magnitude of the applied current. These curves revealed hysteresis loop widths narrower than those obtained under VC mode of operation (see Figure 2). Due to differences in VO$_2$ micro-channel dimensions the device $D_{10}$ (Figure 3(a)) exhibited a smaller hysteresis than the device $D_{20}$ (Figure 3(b)). The ‘S’ NDR shapes observed in Figure 3 is a signature of VO$_2$ two-terminal micro-channel devices [17]. Initially, the channel is in the insulator state and when a threshold current is reached, the channel conductivity starts to rise at the onset of the phase transition and the IMT occurs when the current is further increased. The points $V_{th1}$ and $V_{th2}$ (see Figure 3 (a) and (b)) represents the two threshold voltages for the forward and the backward phase transition, respectively, similar to the VC mode of operation (see Figure 2). The devices exhibited infinite differential resistance between $V_{th1}$ and $V_{th2}$ for increasing (or decreasing) currents. In the CC mode of operation, the current is restricted and that is why the current does not increase sharply at $V_{th1}$; instead, the voltage drops since it is not controlled in the CC mode of operation. Thus, infinite NDR is observed.

The current ‘jumps’ after the phase transition around 1 mA, in the $I$–$V$ curves shown in Figure 3(a) and (b) are possibly associated with additional transformation of a fraction of VO$_2$ domains into the metallic state as the current is further increased. The differences in voltages for increasing and decreasing currents after the IMT, is attributed to reduced hysteresis effect since less heat is generated under CC mode of operation. Figure 4 (a) and (b) show the electrical oscillation waveforms for devices $D_{10}$ and $D_{20}$, respectively. An external resistor, $R_{ext} = 1.5 \ \Omega$ in series with the devices was used in these experiments. The circuit was biased with $I_p = 0.8 \ \text{mA}$ and the measurements were carried out at $T_S = 64 \ ^\circ\text{C}$. Large modulation voltages ($\Delta V_{pp} = 13 \ \text{V}, 8.6 \ \text{V}$) were observed for both devices. We determined waveform oscillation frequencies $f_o = 8.3 \ \text{kHz}$ and $f_o = 5 \ \text{kHz}$ for devices $D_{10}$ and $D_{20}$, respectively (see Figure 4 (a), (b)). The difference in oscillation frequency is attributed to the differences in the channel dimensions on the two devices. Each cycle of oscillation consists of an exponential voltage

![Figure 3. I-V curves for devices D_{10} (a) and D_{20} (b) under CC mode of operation at increasing (I) or decreasing (▲) device current. Measurements were performed with fixed R_{ext} = 4.0 \ \Omega and T_S = 64 \ ^\circ\text{C}. Points V_{th1} and V_{th2} are the threshold voltages corresponding to the forward and the reverse IMT, respectively.](image-url)
build-up across the channel followed by a rapid (~ 1 μs) relaxation when threshold voltage for IMT is reached. The electrical oscillation waveforms in VO₂ micro-channel devices can also be obtained without any external series resistance. Figure 5 shows the spontaneous oscillation between the insulator and metallic states for a device D₁₀ using $I_{SP} = 0.6$ mA and $T_s = 60$ °C without an external series resistance. Such oscillation is triggered for $I_{SP} \geq 0.6$ mA, $I_{SP} = 0.6$ mA is sufficient to induce the IMT but neither insulating nor metallic states are stabilized and hence oscillations are observed. Any lower $I_{SP}$ is unable to induce the IMT and the VO₂ channel remains permanently in the insulating state and no oscillations are observed. For very large $I_{SP}$ the channel transforms permanently into the metallic state and no oscillations are observed either. We determined $\Delta V_{PP} \approx 10$ V and $f_o \approx 9.1$ kHz from the waveform shown in Figure 5. Both Figures 4 and 5 depict CC mode of oscillation. However, the exponentially rising part of the oscillation waveform is steeper (see Figure 5) in this configuration when compared to the oscillation waveforms generated with the external resistor shown in Figure 4 due to a reduced time constant. The higher oscillation frequency is attributed to a faster exponential voltage build-up across the channel. The result shown in Figure 5 indicates that the complexity of prospective oscillator circuits incorporating VO₂ micro-channels can be further reduced by eliminating the need of using external resistors connected to the devices.

3.2 Effect of an external optical excitation on the oscillation waveforms

Fine tuning of the frequency and the peak-to-peak amplitude of the oscillation waveforms under CC mode of operation was achieved using an external optical excitation source to illuminate the VO₂ channels of the devices. A similar voltage and frequency tuning could be also achieved by changing the device temperature. However, using an external laser source, the additional photo-induced heating can be realized at localized regions of the device and this provides further control over the oscillation waveforms. Furthermore, the localized photo-induced heating process can be accomplished much faster than the thermal tuning, which requires heating and temperature stabilization of the entire device package.

Figure 6 (a) and (b) show, respectively, generated waveforms for a D₁₀ device obtained without any external laser ($P_o = 0$) and with a laser excitation power $P_o = 455$ W/cm². In these experiments we have used fixed $I_{SP} = 1$ mA, $R_{ext} = 1.5$ kΩ and $T_s = 60$ °C. At $P_o = 0$ (Figure 6(a)) and $P_o = 455$ W/cm² (Figure 6(b)), we determined, respectively, $f_o = 7.6$ kHz and $f_o = 11.5$ kHz. The change in oscillation frequency is accompanied by changes in $\Delta V_{PP}$. At $P_o = 455$ W/cm² (Figure 6(b)), we determined a reduction in $\Delta V_{PP}$ by 3.2 V when compared to the case of no laser illumination (Figure 6(a)). The oscillation waveform ceased to exist for $P_o > 455$ W/cm². The observed changes in $f_o$
and $\Delta V_{pp}$ with increasing laser power were attributed to changes in threshold voltages $V_{th1}$ and $V_{th2}$ as discussed in section 3.1.

4. Discussions

4.1 Oscillation mechanism and the origin of exponential nature of the waveforms

The origin of the electrical oscillation waveforms shown in Figure 4 is revealed through a careful observation of the $I$–$V$ curves under CC mode of operation shown in Figure 3. Before reaching the IMT threshold voltage $V_{th1}$ the channel has high resistance. During the phase transition, the channel conductivity increases and the voltage drop across channel decreases simultaneously creating the NDR region. The current rises after $V_{th1}$ is reached and the current at this voltage is $I_{th1}$. When biased by a constant current higher than $I_{th1}$ the device voltage oscillates between the voltages $V_{th1}$ and $V_{th2}$. The value of this current ($I_{sp} > I_{th1}$) is the threshold current required to trigger the oscillation. If supplied by a current lower than $I_{th1}$, the device does not oscillate.

Initially the channel is in the insulating state and the voltage across the device increases when supplied by an external current source. This is characterized by the exponentially increasing part of the oscillation waveforms (see Figure 4 (a), (b) and 5). Such voltage build-up is cut-off by the IMT and is marked by the peaks of the waveforms. After the IMT the VO$_2$ channel transforms into the metallic phase with very low resistance and the channel voltage drops abruptly (beyond $V_{th2}$) similar to previous reports [17,18]. Then the channel voltage increases again and the process is repeated cyclically. The exponential build-up of voltage across the micro-channel is analogous to the electrical response of an RC circuit. The two Au/Ti electrodes of the device act as capacitor providing the effective internal capacitance ($C_{osc}$). The physical equivalent circuit for the device comprises of a parallel combination of the channel resistance and the effective capacitance (see inset of Figure 7(a)). The exponentially rising region of the waveforms can be fitted with the following empirical exponential RC circuit charging relation [17]:

$$ V_{channel}(t) = \Delta V_{MO} \left[ 1 - e^{-\left(\frac{t}{\tau}\right)} \right] + V_{th2} \quad (3) $$

where $\Delta V_{MO}$ is the target voltage modulation which is controlled by the voltage supplied by the current source to drive the constant current in the circuit and it is cut off by the phase transition at $V_{th2}$. $\tau$ is the characteristic time constant of the equivalent RC circuit, and $t_o$ is a time-reference shifting parameter for the oscillation time scale. During such exponential voltage build-up, charges appear on the large electrodes whereas a small current flows through the highly resistive VO$_2$ channel. When the voltage across the channel is larger than $V_{th1}$, the channel transforms into the metallic state and the charges rapidly flow through the channel whereas the source voltage is reduced to maintain a constant current in the circuit. In Figure 7(a) we show the non-linear square fitting using (3) for the oscillation waveforms for a D$_{10}$ device with $I_{sp} = 1$ mA and $I_{sp} = 0.6$ mA during the exponential voltage build-up, at $T_\Delta = 60 \, ^\circ\text{C}$. We determined an identical time constant $\tau = 135.7 \, \mu\text{s}$ for both curves but the target voltage modulation is higher for $I_{sp} = 1$ mA. Thus voltage rises faster for $I_{sp} = 1$ mA and a higher oscillation frequency is observed when compared to $I_{sp} = 0.6$ mA. The effect of the external resistance on the oscillation waveform is shown in Figure 7(b) for the same device with $I_{sp} = 0.6$ mA and $T_\Delta = 60 \, ^\circ\text{C}$. The target voltage modulation is identical for both curves but the time constant decreased from 113.4 $\mu$s to 98.9 $\mu$s for the measurements with $R_{ext} = 1.5 \, \text{k}\Omega$ and no external resistor, respectively. The oscillation frequency increased from $f_o = 7.7$ to 9.1 kHz due to a decrease in the time constant when the external resistor is removed. A direct measurement of the devices’ capacitance yielded a value

Figure 6. Electrical oscillation waveforms obtained under CC mode of operation for a D$_{10}$ device at fixed $I_{sp} = 1$ mA, $R_{ext} = 1.5 \, \text{k}\Omega$ and $T_\Delta = 60 \, ^\circ\text{C}$. (a) no laser illumination and (b) illuminated by a laser with $P_\delta = 455 \, \text{W/cm}^2$. (c) Measured oscillation frequencies and (d) peak-to-peak amplitude voltage for a D$_{10}$ device at different laser power densities. The dashed straight lines in (c) and (d) are guides to the eye.
of $\sim 10^{-12}$ F. However, an effective capacitance of $\sim 10^{-9}$ F was determined from the non-linear square fitting of the experimental data. This is attributed to the relatively slow time response ($\sim 100$ µs) and output capacitance ($\sim 10^{-9}$ F) of the power source under the CC mode of operation. This also limited the frequency of the oscillations in our experiments to $\sim 10$ kHz.

The S-type $I$–$V$ curves exhibited by the two-terminal VO$_2$ devices (see Figure 3) are characterized by the two threshold voltages $V_{th1}$ and $V_{th2}$ corresponding to the forward and reverse IMT, respectively. When the device is supplied by a constant current, higher than the aforementioned threshold current, the corresponding voltage across the device cannot increase instantaneously. Instead, it rises exponentially similar to a capacitor charging (see Figures 4–6 and 7(b)). After $V_{th1}$ is reached, the VO$_2$ channel transforms into the metallic state creating a current flow path parallel to the internal capacitor (see inset of Figure 7(a)). A rapid relaxation of the capacitor charge occurs through the highly conductive channel. As a result, the voltage across the channel becomes lower than $V_{th2}$, which is not sufficient to hold it in the metallic state since the current magnitude is limited. As the voltage across the channel drops below $V_{th2}$, the reverse IMT occurs and the channel transforms back into the insulating state. This process is repeated to keep the current constant and then the oscillation is observed. The DC power source supplies a constant current while the voltage changes to drive the same current through the changing channel resistance. Therefore, the oscillation is a consequence of charging and discharging of the internal capacitor due to changes in the VO$_2$ channel resistance. Such oscillation can be modelled using an equivalent circuit approach. We implemented an equivalent circuit model using the SPICE simulation software to model the observed oscillation waveforms in our experiments. Figure 8(a) shows the circuit equivalent model used to generate the oscillatory response under similar biasing conditions [22]. The VO$_2$ micro-channel device is represented by the voltage-controlled resistor $R_{\text{channel}}$ which is a function of the voltage drop ($V_{\text{channel}}$) across the channel. The state of the device (insulator or metallic) is controlled by an ideal op-amp and it is stored inside the output capacitor ($C_o$). The voltage ($V^+$) at the non-inverting terminal is the sum of two dependent voltage sources represented by the following relation [26]:

$$V^+ = V_{th1}\alpha_{V_o} + V_{th2}(1 - \alpha_{V_o})$$

(4)

where $V_o$ is the output voltage of the op-amp. $\alpha_{V_o}$ is a dimensionless parameter that represents the magnitude of $V_o$. The voltage at the inverting terminal is provided by another voltage dependent voltage source $V^- = V_{\text{channel}}$ that represents the voltage drop across the VO$_2$ device. The channel resistance is controlled by the following relation [26]:

$$R_{\text{channel}} = \frac{R_f R_M}{[R_f \delta_{V_c} + R_M(1 - \delta_{V_c})]}$$

(5)

where $R_f$ and $R_M$ represent the channel resistances in the insulating and in the metallic states, respectively, and $V_c$ is the voltage drop across $C_o$. $\delta_{V_c}$ is another dimensionless parameter that represents the magnitude of $V_c$. Initially, $\alpha_{V_o} = 1$ and $\delta_{V_c} = 0$ when $V_o = 1$ V and $V_c = 0$ V. The device is in the insulator state and the channel resistance is $R_f$. $V^+ = V_{th1}$ is the threshold voltage to induce the IMT. When an increasing voltage is applied to the device and the voltage across the channel resistance ($R_{\text{channel}}$) exceeds $V_{th1}$ the op-amp output changes to 0 V and this triggers the resistance switching. In this state, the aforementioned parameters take the values $\alpha_{V_o} = 0$ and $\delta_{V_c} = 1$. The channel resistance changes to $R_{\text{channel}} = R_M$. In the metallic state, the voltage at the non-inverting terminal becomes $V^- = V_{th2}$ and the reverse IMT occurs at a lower threshold voltage thus simulating the hysteresis effect in VO$_2$. Discharging of the internal capacitor reduces the voltage drop across the $R_{\text{channel}}$. When $V_{\text{channel}}$ drops below $V_{th2}$ the op-amp output becomes 1 V again and
the capacitor voltage becomes $V_C = 0$ V. Thus, the reverse resistance switching occurs and the channel resistance becomes $R_I$ again. This process is repeated and produces the voltage oscillation. A comparison between the oscillation waveform generated from the simulation and experiment for the device D10 using $I_{SP} = 0.6$ mA is shown in Figure 8(b). In this simulation, the metallic and insulating state resistances used were $R_M = 400$ Ω and $R_I = 50$ kΩ, respectively and the threshold voltages used were $V_{th1} = 10.7$ V and $V_{th2} = 2.8$ V. These values were determined experimentally. The product $R_{osc} = \tau_o$ is the time constant of the RC circuit in the output of the op-amp (see Figure 8(a)). $\tau_o$ works as a fitting parameter for the time scale of the oscillation waveform generated by the simulation. The forward and reverse switching between insulating and metallic states in the channel are not instantaneous but rather depends on the device dimensions. $\tau_o$ was chosen appropriately to take this into account and to accurately reproduce the experimental oscillation waveforms.

### 4.2 Optical tuning

The external optical excitation changes the transition voltage threshold by reducing the VO$_2$ channel resistance. The frequency of the oscillation increases and the peak-to-peak voltage decreases due to the reduction of the threshold voltage. The influence of the optical excitation on the oscillation frequency was shown in Figure 6. The oscillation frequency $f_o \approx 7.6$ kHz is observed in device D10 without optical excitation (Figure 6(a)) and under optical illumination with $P_o \approx 455$ W/cm$^2$, it increases to $f_o \approx 11.4$ kHz (Figure 6(b)). The oscillation ceases to occur for $P_o > 455$ W/cm$^2$. Such optical power density further heats the device and transform the VO$_2$ channel into the metallic state and therefore the oscillations were no longer observed. The exponential part of voltage build-up across the channel controls the oscillation frequency and can be approximately described by the following empirical relation.

$$\Delta V_{channel}(t) \propto \left(1 - e^{-t/\tau}\right)$$

where $\tau$ is the characteristic time constant for exponential voltage rise. The voltage rise is cut off when $\Delta V_{channel}(t)$ reaches the threshold voltage, $V_{th1}$. The external optical illumination reduces the voltage rise time by lowering $V_{th1}$. Thus, an increased oscillation frequency was observed. A linear dependence in the oscillation frequency with the optical power density was determined from Figure 6(c). At elevated temperatures, only a part of the resistance hysteresis loop is accessed under varying optical excitation conditions where such dependence is linear. The peak-to-peak voltage was reduced by photo-exciting the device micro-channel and a voltage peak-to-peak amplitude change from 10.2 V to 7.0 V (see Figure 6(d)) was determined when the laser power density was varied from $P_o = 0$ to $P_o = 455$ W/cm$^2$, respectively.

### 5. Conclusions

In summary, we fabricated, characterized, and simulated VO$_2$ planar micro-channel oscillators with tunable characteristics. Voltage and current controlled phase transitions were investigated in devices with different microchannel dimensions. Generated waveforms under CC mode of operation with large voltage modulation were achieved by controlling the current in the NDR region of
the device response. The spontaneous electrical oscillation originates from the continuous change in the device channel resistance. An appropriate size of parasitic capacitance was achieved in the device architecture to stabilize the electrical oscillations. We demonstrated waveform generation without the need of any external resistive, capacitive or inductive components or any external pulsed current excitation. The oscillation frequency of the two-terminal micro-channel devices can be further significantly increased using low resistivity VO\textsubscript{2} material and faster time response of the power supply. Optically induced threshold voltage reduction enabled waveform amplitude control and fine frequency tuning in the investigated devices. The oscillation waveforms generated using an equivalent circuit model revealed a good agreement with the experimental results.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

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