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Full paper

Impact-activated programming of electro-mechanical resonators through ferroelectret nanogenerator (FENG) and vanadium dioxide

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ABSTRACT

Ferroelectret Nanogenerators (FENG) devices were introduced recently as promising flexible devices for energy harvesting and microphone/loud-speaker applications. Vanadium dioxide (VO_2) thin films, on the other hand, have been demonstrated to enable large frequency tunability of miniaturized electro-mechanical structures, which are commonly integrated in transceiver and communication systems. In this work, we integrate these two technologies, to show a system where an electric pulse, supplied by the FENG can be used to tune the resonant frequency of VO_2-based micro-electro-mechanical structures. Furthermore, due to the VO_2's hysteretic behavior, the applied pulse also programs the tuned frequency, allowing for different frequency states in the device for a single applied DC bias. It is found that the tuning of the frequency states is determined by the supplied energy, and the programming is more efficient for larger, shorter pulses –even if the duration of the pulse is shorter than the system's thermal time constant. We explore two different mechanical structures, bridge and cantilever. A wider tuning range is found for the bridge structure (22%), which is due to the larger frequency sensitivity with stress for this configuration. The tuning/programming action uses harvested mechanical energy, which could come from the user. The potential use of the developed system as an accelerometer or impact sensor for monitoring brain injuries in contact-sports is discussed.

Programming resonant frequency states in a mechanical structure allows for the operation of a single device in multiple frequency channels. This not only broadens the spectrum of applications for the device, but also reduces interference, noise, and enables anti-jamming in communication systems. The tuning actuation required for programming particular states in miniaturized electro-mechanical devices has typically been achieved by using the thermal expansion coefficient of the structural materials and the structure's geometry to generate stress patterns that influence the dynamic behavior of the device [1–4]. More recent advances have exploited the changes in the properties of phase-change materials to generate significant stress, which produce shifts in the resonant frequency of mechanical structures [?] [5–8]. One of the most promising smart materials used for applications requiring tunable performance is vanadium dioxide (VO_2), which has a solid-solid phase transition near 68 °C that comes with drastic changes in a plurality of the material's properties; making it the smart material with the lowest transition temperature [9], and therefore the ideal candidate for low-power actuation. VO_2's multifunctionality has allowed for the tuning of electrical [10–12], optical [13–16], mechanical [17,18] properties; and for the programming of resonant frequency states [19,20]. However, in all these cases, the tuning action and programming capability has been done through external sources that require the constant presence of an electrical power source. NanoGenerators provide an alternative to this. They have been heavily studied recently, and have been the focus of multiple efforts for the development of self-powered devices [21,22].

In this paper, we present a new method for providing the required actuation for tuning/programming frequency states in VO_2 electro-mechanical structures. The method does not require external equipment for providing the electric pulse, and thus, it does not require an external power source during the programming action. This is accomplished by combining the use of the tuning capability of VO_2 thin film coatings with the recently demonstrated FerroElectret NanoGenerator (FENG) device [23–26]. The results shows that tuning/programming can be accomplished by very short pulses –shorter than the device's thermal time constant. In order to understand the energy requirements for

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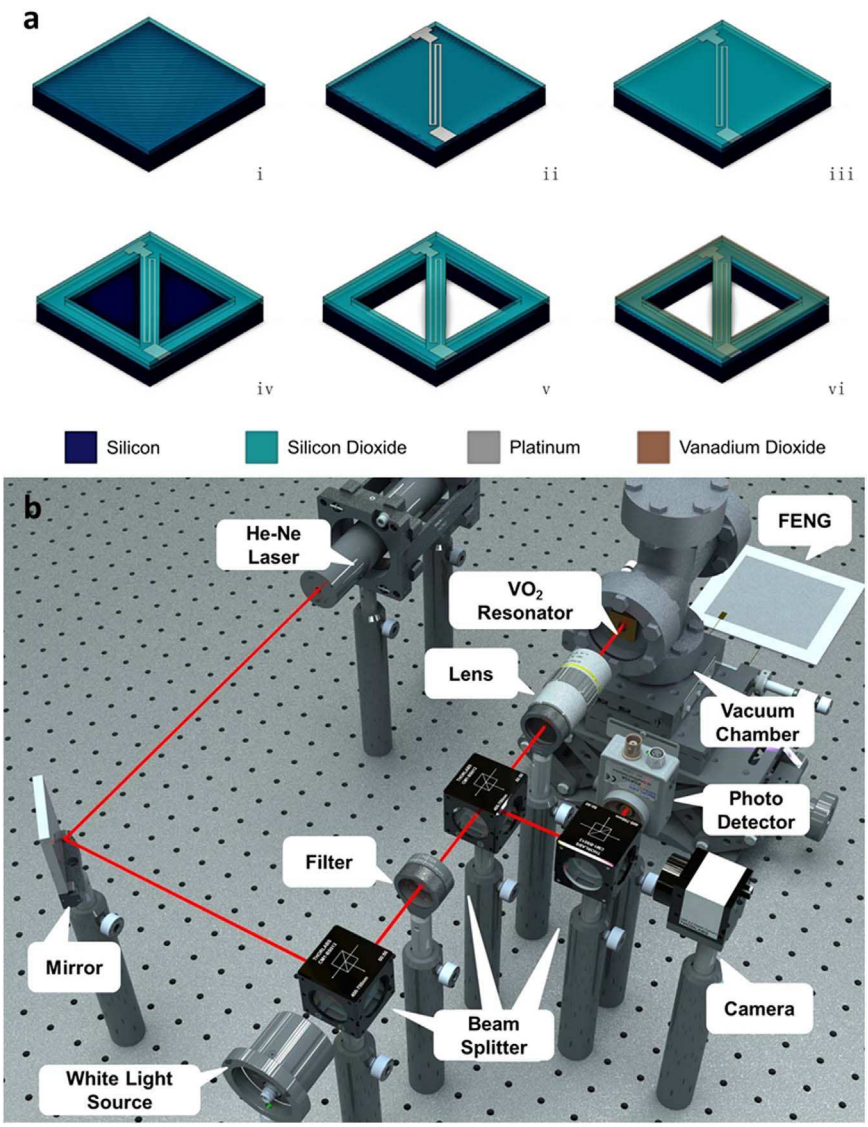

Fig. 1. (a) Fabrication flow of VO_2-based electro-mechanical resonator (bridge structure): i) LTO (Low Temperature Oxidation) of SiO_2 layer on Si substrate; ii), Thermal evaporation of heater trace; iii), LTO deposition of second layer SiO_2; iv), Dry etching of SiO_2; v), Structure released by XeF_2; vi), PLD deposition of VO_2. (b) Schematic of optical testing setup for measuring resonant frequency.

actuation, we performed experiments where a capacitor was charged by the FENG, and the tuning/programming actuation was provided by the capacitor discharge through the monolithically integrated resistive heaters in the resonator structure. Furthermore, it is also demonstrated that a single impact provides enough energy to tune the resonant frequency of a bridge structure. The frequency difference between the programmed states is much larger in the bridge structure, due to the larger built-in thermal stress in this clamped-clamped structure.

The fabrication process for the resonator is shown in Fig. 1a. The resonant frequency of the resonators was measured by the laser beam deflection method [27,28], using the setup shown that is schematically described in Fig. 1b. Details on the resonator and FENG device, as well as the testing set-up are provided in the Supplementary Information. The assembled system allows for tuning of the VO_2-based resonators (heating and cooling of the device) by two methods; (i) Using only conductive heating through a proportional-integral-derivative (PID) temperature controller connected to the Peltier heater and Pt temperature sensor attached to the sample, and (ii) Using resistive heating (i.e. joule heating) through the Pt/Ti integrated metal traces. The first method was used for calibration and film characterization, while the second method was used for the programming experiments. The temperature of the VO_2-based resonators was increased by sending a DC current through the Pt/Ti heater. As this temperature moves across the phase transition of VO_2 the resonant frequency of the micro-electro-mechanical structure shifts abruptly, following the hysteretic behavior of VO_2 similar to the resistance curve shown in Fig. S3b (see Supplementary Information). A series of experiments were performed in order to characterize the FENG/VO_2 integration and find the conditions necessary for tuning/programming from a single strike on the FENG device. These preliminary experiments are discussed next, and were designed to start by finding the time constant of the system and energy requirements.

The testing configuration consisted on connecting the device's metal heater to a DC current source which provided a pre-heating current to the VO_2-based resonator (see Fig. 2a). The pre-heating level was selected at the point where the resonant frequencies between the heating and cooling major hysteretic curves have the largest difference (see Figs. 3a and 4a). A capacitor was then charged by the FENG device through a rectifier. A single-pole-single-throw switch was used to avoid capacitor leakage after charging. Once the capacitor was charged, the discharge current pulse was added to the pre-heating current. The temperature increase due to the current pulse was large enough to heat the structure across the phase transition. When the pulse ended, the temperature of the sample returned to the pre-heating value, but this time following the cooling curve of the hysteresis curve. Thus, the resonant frequency before and after the pulse correspond to the values in the heating and cooling curves, respectively. Videos 1 and 2 in Supplementary Information show the experiments for cantilever and bridge

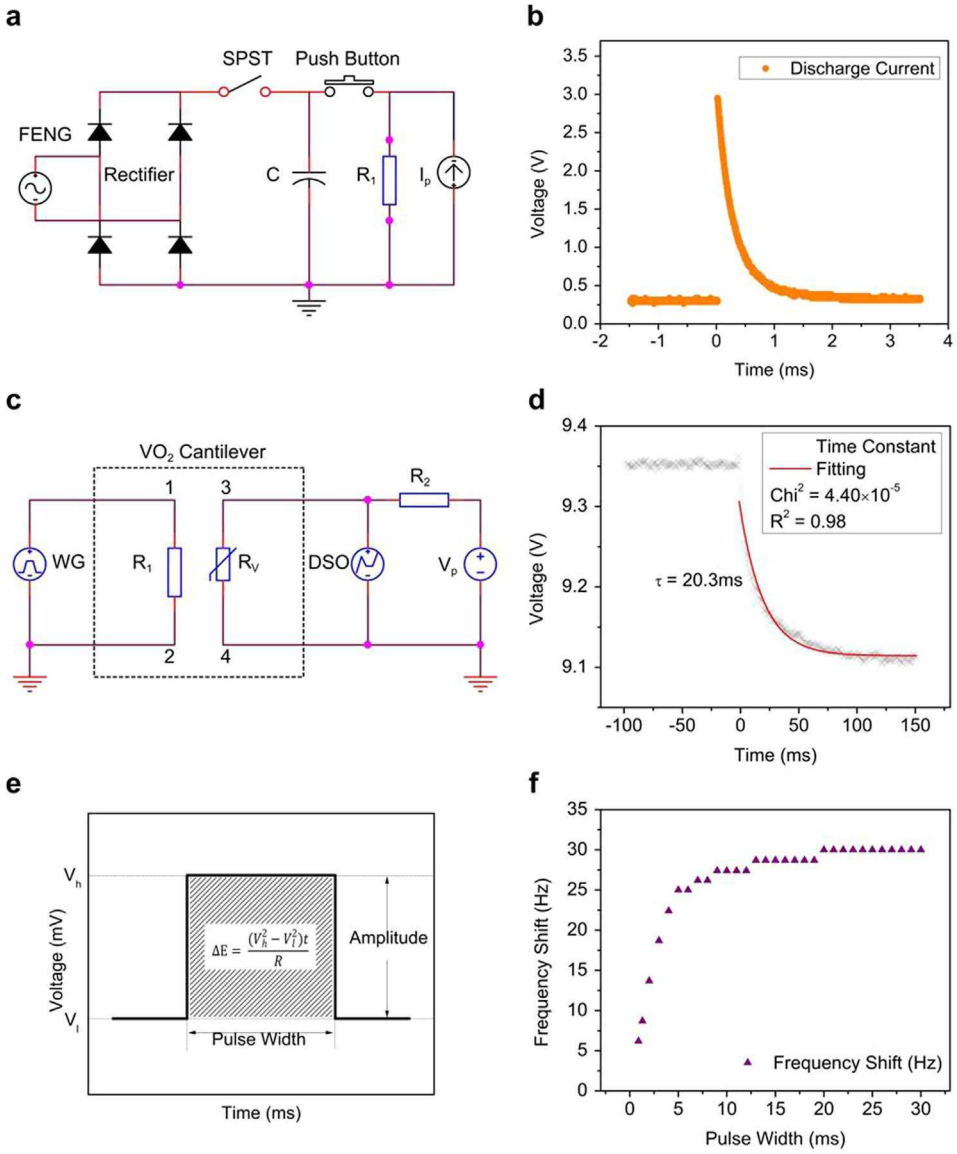

Fig. 2. (a) Circuit of resonant frequency programmability by combing VO_2-based resonator and FENG device. C is the capacitor of 1 μF, R_1 is the resistance of the heater (252 and 228 Ω for the cantilever and bridge, respectively), I_p is the pre-heating current (1 and 1.22 mA for the cantilever and bridge structures, respectively). (b) Voltage profile of the discharge current across the heater. (c) Circuit used for measuring the time constant. A wave-function generator (WG) is connected to the heater R_1. The VO_2 film (R_V)is connected to a resistor (R_2), a pre-heating voltage source (V_p), and an oscilloscope (DSO). (d) Thermal time constant of the VO_2-based cantilever. (e) Schematic of the rectangular pulse supplied by the WG for time-constant and energy calculation experiments. (f) Frequency shift as the function of the pulse width.

structures.

In order to find the conditions of the tunning current pulse for increasing the sample's temperature across the phase transition, it is necessary to know the system's response time. The dynamics of the system is governed by two main processes (thermal and mechanical), and each one has a corresponding time constant. The thermal process is the mechanism by which the current pulse increases the temperature of the sample, while the mechanical process is the mechanism by which the system responds to the phase change of in the VO_2 film. The relation between the thermal time constant and the mechanical time constant can be described as follows:

$$\tau' = \tau_T + \tau_M, \quad (1)$$

where τ_M is the mechanical time constant, τ_T is the thermal time constant and τ', is the response time of the device to the new thermal equilibrium. The thermal time constant is mainly determined by how fast the external heat can be distributed in the device [29,30]. The thermal process is the slowest of the two [31–33] and thus, it will determine the time response of the entire system.

Since the changes in the structural and electrical properties of VO_2 across the phase transition have similar time constants [5,34–36], the thermal time constant of the system can be obtained by simply applying a current pulse and monitoring the change in resistance of the VO_2 film. The measurement setup is shown schematically in Fig. 2c, and explained in more detail in the Supplementary Information. In this experiment, the thermal time constant was defined as the time required for the device to respond when the current was increased from the preheated level of 1–1.7 mA. The measured thermal time constant of this 550 μm long VO_2-based cantilever was 20.3 ms, (see Fig. 2d). To validate the measured time constant for the electro-mechanical system, rectangular pulses of same amplitude but varying width were applied, while the resonant frequency shift was measured. As the pulse width was increased, the frequency shift also increased until the frequency shift reached a maximum value. Thus, the minimum width of the pulse that was able to obtain the maximum frequency shift should be approximately the value of the time constant. The frequency shift as a function of the pulse width is plotted in Fig. 2f. The thermal time constant in this case was estimated to be 21 ms, which is very close to the value determined in Fig. 2d.

The resonant frequency of the bridge as a function of the current is plotted in Fig. 4a. The programmability of the resonant frequency was achieved by first apply a DC current to a pre-heated level where the heating curve and the cooling curve have the maximum separation [37–39]. A transient current pulse was then induced in order to

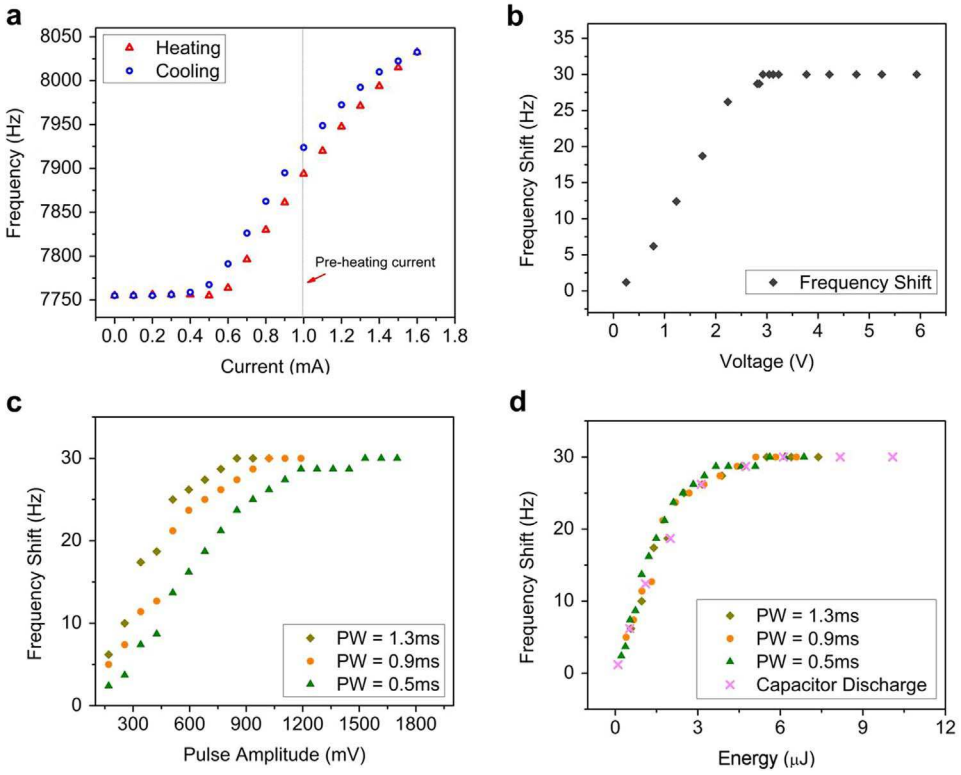

Fig. 3. Tuning and programming frequency states in cantilever structures. (a) Hysteretic major resonant frequency loops for cantilever structure as a function of the current. (b) Frequency shift as a function of the voltage in the capacitor before discharge pulse. (c) Frequency shift as a function of pulse amplitude for three different pulse widths (PW). (d) Frequency shift as a function of energy delivered by the pulse.

complete the phase transition in the VO_2 film and switch the resonant frequency from the heating curve to the cooling curve. Even though the single layer FENG device is able to generate large open circuit voltage, the short circuit current is still in the scale of μ A. Thus, directly connecting a single layer FENG device to the resonator does not produce enough temperature increase to cross the phase transition completely. Therefore, the single layer FENG device was stacked to 7 layers, which amplified the output to 7 times larger than the single layer device [24]. Second, a capacitor was previously charged by the FENG device through a rectifier to a level high enough to go through the phase

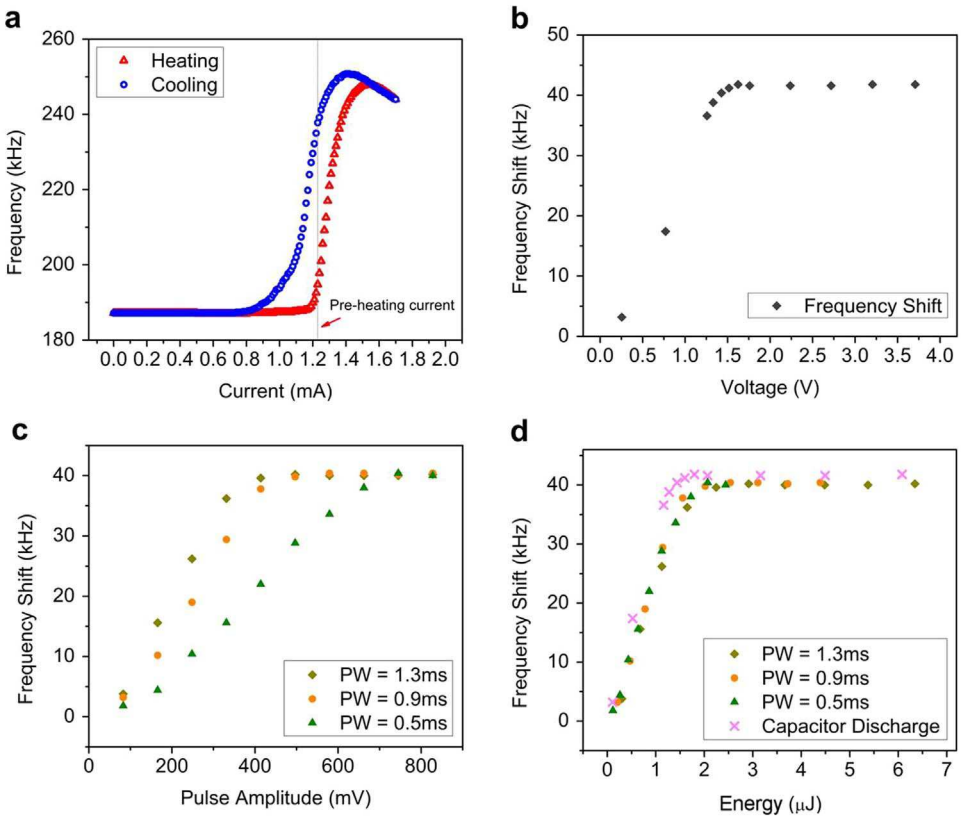

Fig. 4. (a) Hysteretic major resonant frequency loops for bridge structure as a function of the current. (b) Frequency shift as a function of the voltage in the capacitor before discharge. (c) Frequency shift as a function of pulse amplitude for three different pulse widths (PW). (d) Frequency shift as a function of energy delivered by the pulse.

transition completely. Then, the stored energy was released in the form of discharge current for tuning action by using a push-button switch. The current pulse used for the tuning can be determined by the following equation:

$$I = \frac{V_0}{R} e^{-\frac{t}{RC}} + I_p, \tag{2}$$

where V_0 is the voltage charged to the capacitor, R is the resistance of the heater in the cantilever, C is the capacitance of the capacitor and I_p is the pre-heating current. In this experiment, the pre-heated current level was chosen to be 1 mA where the resonant frequency separation between the heating curve and the cooling curve is 30 Hz. The capacitor was previously charged to different voltage levels, and then the discharge current was induced for the tuning. This results in pulses of different amplitude, but same duration, since the time constant remained unchanged. As shown in Fig. 3b, the resonant frequency shift increases with the voltage stored in the capacitor. This suggests that the tuning/programming of the resonant frequency in the devices is determined by the supplied energy. The maximum frequency shift was obtained when the capacitor was charged to 2.9 V.

As discussed earlier, the thermal time constant of the cantilever is approximately 20.3 ms. This means that in order to get the maximum frequency shift, the applied current pulse should be at least 20 ms. However, the discharge current pulse used for the tuning in this experiment has the decay time constant of around 0.27 ms and the transient current only lasts about 1.3 ms. Although the pulse width (PW) was much shorter than the time constant of the device, the transient current still provided enough energy for the resonant frequency to completely across the phase transition region. This finding is crucial for the use of a single strike on a FENG device for programming action. The energy released from the capacitor to the heater can be determined by:

$$\Delta E = \frac{1}{2} C (V_0^2 - V_1^2), \tag{3}$$

where V_1 is the voltage of the capacitor after discharging. To confirm that the tuning mechanism is determined by the supplied energy –independently on how fast was the energy delivered– the following experiment was performed. Instead of applying the RC discharge current, three rectangular pulses of different widths were applied from a waveform generator. The frequency shift as a function of the pulse amplitude was measured (see Fig. 3c). The maximum frequency shift was achieved by the different rectangular pulses respectively at different amplitudes. The energy delivered by the rectangular pulses can be calculated by using the parameters shown in Fig. 2e:

$$\Delta E = \frac{(V_h^2 - V_l^2)t}{R}, \tag{4}$$

where R is the resistance of the heater, V_h is the high voltage, V_l is the low voltage, and t is the width of the pulse. Fig. 3d shows the resonant frequency shift as a function of the energy delivered by three different pulses, and by the discharge current from the capacitor. All four curves show very similar behavior. This confirms that the tuning mechanism is dominated by the supplied energy. The energy required for tuning this 550 μm VO_2-based cantilever is about 5.1 μJ. Moreover, if the cantilever was applied a rectangular pulse of $V_h = 578$ mV and $V_l = 280$ mV (considering the TCR of the heater is around 33.5 Ω/mA^2), the duration of the pulse should be at least 20 ms. In this case, the energy consumed by the cantilever is about 18.2 μJ. This larger energy consumption is probably due to the larger heat dissipation during a longer tuning process. Thus, it is more energy-efficient to apply a shorter pulse with higher amplitude.

The resonant frequency programmability was also demonstrated for a 300 μm long VO_2-based micro-electro-mechanical bridge structure. The resonant frequency as a function of current was plotted in Fig. 4a. The current step here was chosen to be 0.01 mA since the bridge structure is more sensitive to the stress [?], which also translates into a much larger tuning frequency than the cantilever structure (32% for the bridge, and 4% for the cantilever). For the bridge structure, the pre-heating current was 1.22 mA. The resonant frequency tuning based on the RC discharge current is illustrated in Fig. 4b. The frequency shift increases with the voltage in the capacitor, and saturates at around 1.6 V. The maximum resonant frequency shift was measured to be around 42 kHz, which is consistent with the value estimated from Fig. 4a. This indicates that a voltage of 1.6 V in the capacitor provided enough energy to completely cross the phase transition region (for a pre-heating current of 1.22 mA). The thermal time constant was also measured for the bridge using the same method used for the cantilever. The value was determined to be around 9 ms, which is much shorter than the cantilever. This is due to two reasons: (i) the bridge has one more anchor than the cantilever, which represents a more uniform temperature distribution and one more heat sink that helps dissipate temperature; and (ii) the bridge is shorter than the cantilever, which means the bridge has less thermal mass and therefore the response time is shorter.

Energy was also found to be the tuning parameter for the bridge structures. Figs. 4c–d show the frequency shift as a function of rectangular pulse amplitude and energy, respectively. The same pattern shown in Figs. 3c–d was observed, and the minimum energy required for inducing a frequency shift of around 30 Hz was 5.11 μJ. In Fig. 4d, there is a small discrepancy between the discharge current and the rectangular pulse. This can be attributed to the high sensitivity to stress. The rectangular pulses were provided by the waveform generator as a voltage signal. The energy consumption for programming (i.e. dynamic power consumption) required by the bridge was estimated to be 2.07 μJ. A more detailed discussion on the difference between the tunability for both structures can be found in the Supplementary Information, together with complementary Finite Element Method simulations.

As discussed above, the tuning/programming of multiple frequency states can be achieved by very short pulses, as long as the delivered energy is enough. Thus, practical applications could include impact sensors, such as those needed for monitoring injuries in high-contact sports, where a single, quick (but intense) impact generates enough energy to program a different frequency state. The flexibility of the FENG device and the size of the resonator structure enables the required flexibility for the integration of this system in wearables or even textiles. The Supplementary Information includes the discussion of an application note for monitoring head injuries, and shows how a single impact can transition the VO_2-based actuator completely, and program a frequency state about 40 kHz different than the pre-heated state.

To summarize, the programmability of frequency states in electromechanical resonators was demonstrated by combing VO_2-based resonators (550 μm cantilever and 330 μm bridge), with a stacked FENG device. The tuning/programming action was achieved by first applying a DC current to a pre-heated level where the frequency separation between the heating curve and the cooling curve is the maximum. Then, a short energy pulse was applied to program a different resonant frequency state in the structure. It was found that shorter pulses with larger amplitudes are more energy-efficient than longer pulses of smaller amplitudes. This finding enables the use of a single strike on a FENG device to program a resonant frequency state. The pulse could also come from a capacitor charged by multiple small impacts - as long as the supplied energy is above the minimum threshold for actuation. This threshold will depend mainly on the type of structure and pre-heating level. The maximum tuning range for the cantilever was around 30 Hz (0.38%) while it was about 40 kHz (22%) for the bridge since the resonant frequency of bridge is more stress sensitive.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.nanoen.2017.10.066.

References

[1] Melburne C. LeMieux, Michael E. McConney, Yen-Hsi Lin, Srikanth Singamaneni, Hao Jiang, Timothy J. Bunning, Vladimir V. Tsukruk, Polymeric nanolayers as actuators for ultrasensitive thermal bimorphs, Nano Lett. 6 (4) (2006) 730–734 (PMID: 16608273).

[2] John P. Mathew, Raj Patel, Abhinandan Borah, Carina B. Maliakkal, T.S. Abhilash, T.S. Abhilash, Mandar M. Deshmukh, Nanoscale electromechanics to measure thermal conductivity, expansion, and interfacial losses, Nano Lett. 15 (11) (2015) 7621–7626.

[3] Todd Remtema, Liwei Lin, Active frequency tuning for micro resonators by localized thermal stressing effects, Sens. Actuators A: Phys. 91 (3) (2001) 326–332.

[4] Richard R.A. Syms, Electrothermal frequency tuning of folded and coupled vibrating micromechanical resonators, J. Microelectromech. Syst. 7 (2) (1998) 164–171.

[5] Nicola Manca, Luca Pellegrino, Teruo Kanki, Syouta Yamasaki, Hidekazu Tanaka, Antonio Sergio Siri, Daniele Marré, Programmable mechanical resonances in mems by localized joule heating of phase change materials, Adv. Mater. 25 (44) (2013) 6430–6435.

[6] Jinbo Cao, Wen Fan, Qin Zhou, Erica Sheu, Aiwen Liu, C. Barrett, J. Wu, Colossal thermal-mechanical actuation via phase transition in single-crystal vo2 microcantilevers, J. Appl. Phys. 108 (8) (2010) 083538.

[7] Alexander Tselev, John D. Budai, Evgheni Strelcov, Jonathan Z. Tischler, Andrei Kolmakov, Sergei V. Kalinin, Electromechanical actuation and current-induced metastable states in suspended single-crystalline vo2 nanoplatelets, Nano Lett. 11 (8) (2011) 3065–3073.

[8] Kai Liu, Chun Cheng, Zhenting Cheng, Kevin Wang, Ramamoorthy Ramesh, Junqiao Wu, Giant-amplitude, high-work density microactuators with phase transition activated nanolayer bimorphs, Nano Lett. 12 (12) (2012) 6302–6308.

[9] S.D. Ha, Y. Zhou, A.E. Duwel, D.W. White, S. Ramanathan, Quick switch: strongly correlated electronic phase transition systems for cutting-edge microwave devices, IEEE Microw. Mag. 15 (6) (2014) 32–44.

[10] T. Driscoll, G.O. Andreev, D.N. Basov, S. Palit, S.Y. Cho, N.M. Jokerst, D.R. Smith, Tuned permeability in terahertz split-ring resonators for devices and sensors, Appl. Phys. Lett. 91 (6) (2007) 062511.

[11] Ilya V. Shadrivov, Nina A. Zharova, Alexander A. Zharov, Yuri S. Kivshar, Defect modes and transmission properties of left-handed bandgap structures, Phys. Rev. E 70 (4) (2004) 046615.

[12] Suhas Kumar, Matthew D. Pickett, John Paul Strachan, Gary Gibson, Yoshio Nishi, R.Stanley Williams, Local temperature redistribution and structural transition during joule-heating-driven conductance switching in vo2, Adv. Mater. 25 (42) (2013) 6128–6132.

[13] Tom Driscoll, Hyun-Tak Kim, Byung-Gyu Chae, Bong-Jun Kim, Yong-Wook Lee, N. Marie Jokerst, Sabarni Palit, David R. Smith, Massimiliano Di Ventra, Dimitri N. Basov, Memory metamaterials, Science 325 (5947) (2009) 1518–1521.

[14] Shengxiang Wang, Lei Kang, Douglas H. Werne, Hybrid resonators and highly tunable terahertz metamaterials enabled by vanadium dioxide (vo2), Sci. Rep. 7 (2017).

[15] Horacio Coy, Rafmag Cabrera, Nelson Sepulveda, Felix E. Fernandez, Optoelectronic and all-optical multiple memory states in vanadium dioxide, J. Appl. Phys. 108 (11) (2010) 113115.

[16] Tom Driscoll, S. Palit, Mumtaz M. Qazilbash, Markus Brehm, Fritz Keilmann, Byung-Gyu Chae, Sun-Jin Yun, Hyun-Tak Kim, SY Cho, N. Marie Jokerst, et al., Dynamic tuning of an infrared hybrid-metamaterial resonance using vanadium dioxide, Appl. Phys. Lett. 93 (2) (2008) 024101.

[17] Armando Rua, Felix E. Fernandez, Nelson Sepulveda, Bending in vo2-coated microcantilevers suitable for thermally activated actuators, J. Appl. Phys. 107 (7) (2010) 074506.

[18] Aaron Holsteen, In Soo Kim, Lincoln J. Lauhon, Extraordinary dynamic mechanical response of vanadium dioxide nanowires around the insulator to metal phase transition, Nano Lett. 14 (4) (2014) 1898–1902.

[19] Emmanuelle Merced, Rafmag Cabrera, Noraica Davila, Felix E. Fernandez, Nelson Sepulveda, A micro-mechanical resonator with programmable frequency capability, Smart Mater. Struct. 21 (3) (2012) 035007.

[20] Luca Pellegrino, Nicola Manca, Teruo Kanki, Hidekazu Tanaka, Michele Biasotti, Emilio Bellingeri, Antonio Sergio Siri, Daniele Marré, Multistate memory devices based on free-standing vo2/tio2 microstructures driven by joule self-heating, Adv. Mater. 24 (21) (2012) 2929–2934.

[21] Zhong Lin Wang, On maxwell's displacement current for energy and sensors: the origin of nanogenerators, Materials Today, 2017.

[22] Zhong Lin Wang, Tao Jiang, Liang Xu, Toward the blue energy dream by triboelectric nanogenerator networks, Nano Energy, 2017.

[23] Wei Li, David Torres, Ramón Díaz, Zhengjun Wang, Changsheng Wu, Chuan Wang, Zhong Lin Wang, Nelson Sepúlveda, Nanogenerator-based dual-functional and self-powered thin patch loudspeaker or microphone for flexible electronics, Nat. Commun. 8 (2017).

[24] Wei Li, David Torres, Tongyu Wang, Chuan Wang, Nelson Sepúlveda, Flexible and biocompatible polypropylene ferroelectret nanogenerator (feng): on the path toward wearable devices powered by human motion, Nano Energy 30 (2016) 649–657.

[25] Zhenhua Luo, Dibin Zhu, Junjie Shi, Steve Beeby, Chunhong Zhang, Plamen Proynov, Bernard Stark, Energy harvesting study on single and multilayer ferroelectret foams under compressive force, IEEE Trans. Dielectr. Electr. Insul. 22 (3) (2015) 1360–1368.

[26] Fouad Belhora, Abdelowahed Hajjaji, El Fatnani, Fatima Zahra, Abdelkader Rjafallah, Daniel Guyomar, et al., Energy harvesting using hybridization of dielectric nanocomposites and electrets, Polym. Adv. Technol. 26 (6) (2015) 569–573.

[27] Daniel Ramos, Maria Arroyo-Hernandez, Eduardo Gil-Santos, Hien Duy Tong, Cees Van Rijn, Montserrat Calleja, Javier Tamayo, Arrays of dual nanomechanical resonators for selective biological detection, Anal. Chem. 81 (6) (2009) 2274–2279.

[28] P.M. Kosaka, J. Tamayo, E. Gil-Santos, J. Mertens, V. Pini, N.F. Martínez, O. Ahumada, M. Calleja, Simultaneous imaging of the topography and dynamic properties of nanomechanical systems by optical beam deflection microscopy, J. Appl. Phys. 109 (6) (2011) 064315.

[29] Rafmag Cabrera, Emmanuelle Merced, Nelson Sepúlved, Félix E. Fernández, Dynamics of photothermally driven vo2-coated microcantilevers, J. Appl. Phys. (2011).

[30] Emmanuelle Merced, Noraica Dávila, David Torres, Rafmag Cabrera, Félix E. Fernández, Nelson Sepúlveda, Photothermal actuation of v o2: Cr-coated microcantilevers in air and aqueous media, Smart Mater. Struct. 21 (10) (2012) 105009.

[31] Tongyu Wang, David Torres, Félix E. Fernández, Chuan Wang, Nelson Sepúlveda, Maximizing the performance of photothermal actuators by combining smart materials with supplementary advantages, Sci. Adv. 3 (4) (2017) e1602697.

[32] Tongyu Wang, David Torres, Félix E. Fernández, Andrew J. Green, Chuan Wang, Nelson Sepúlveda, Increasing efficiency, speed, and responsivity of vanadium dioxide based photothermally driven actuators using single-wall carbon nanotube thin-films, ACS Nano 9 (4) (2015) 4371–4378.

[33] He Ma, Jiwei Hou, Xuewen Wang, Jin Zhang, Zhiquan Yuan, Lin Xiao, Yang Wei, Shoushan Fan, Kaili Jiang, Kai Liu, Flexible, all-inorganic actuators based on vanadium dioxide and carbon nanotube bimorphs, Nano Lett. 17 (1) (2016) 421–428.

[34] Kunio Okimura, Nurul Hanis Azhan, Tetsuya Hajiri, Shin-ichi Kimura, Mustapha Zaghrioui, Joe Sakai, Temperature-dependent raman and ultraviolet photoelectron spectroscopy studies on phase transition behavior of vo2 films with m1 and m2 phases, J. Appl. Phys. 115 (15) (2014) 153501.

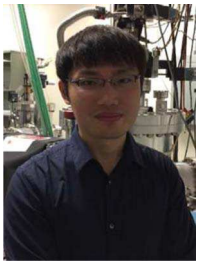
[35] Andrea Cavalleri, Th Dekorsy, Henry HW Chong, Jean-Claude Kieffer, Robert W. Schoenlein, Evidence for a structurally-driven insulator-to-metal transition in vo 2: A view from the ultrafast timescale, Phys. Rev. B 70 (16) (2004) 161102.

[36] Mumtaz M. Qazilbash, A. Tripathi, A.A. Schafgans, Bong-Jun Kim, Hyun-Tak Kim, Zhonghou Cai, M.V. Holt, J.M. Maser, Fritz Keilmann, O.G. Shpyrko, et al., Nanoscale imaging of the electronic and structural transitions in vanadium dioxide, Phys. Rev. B 83 (16) (2011) 165108.

[37] Kota Ito, Kazutaka Nishikawa, Hideo Iizuka, Multilevel radiative thermal memory realized by the hysteretic metal-insulator transition of vanadium dioxide, Appl. Phys. Lett. 108 (5) (2016) 053507.

[38] Yuriy V. Pershin, Massimiliano Di Ventra, Memory effects in complex materials and nanoscale systems, Adv. Phys. 60 (2) (2011) 145–227.

[39] Sungyoul Choi, Bong-Jun Kim, Yong Wook Lee, Yong Sik Lim, Jeongyong Choi, Hyun-Tak Kim, Control of current-jump induced by voltage, temperature, light in p-type gaas: programmable critical temperature sensor, Appl. Phys. Lett. 95 (23) (2009) 231910.



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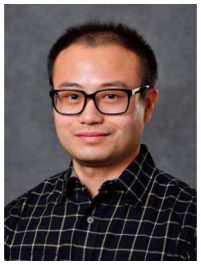

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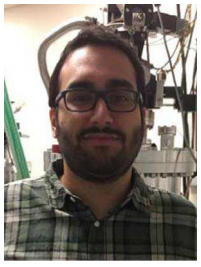

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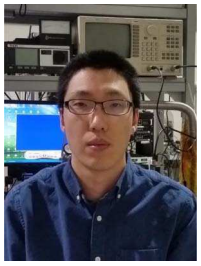

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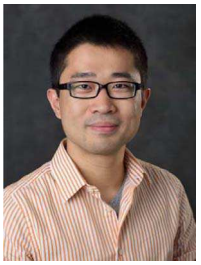

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