SUPPLEMENTARY INFORMATION

Electric Field assisted Resonance Frequency Tuning in Free Standing Nanomechanical Devices for the Application in Multistate Switching using Phase Change Material

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S1: PLD

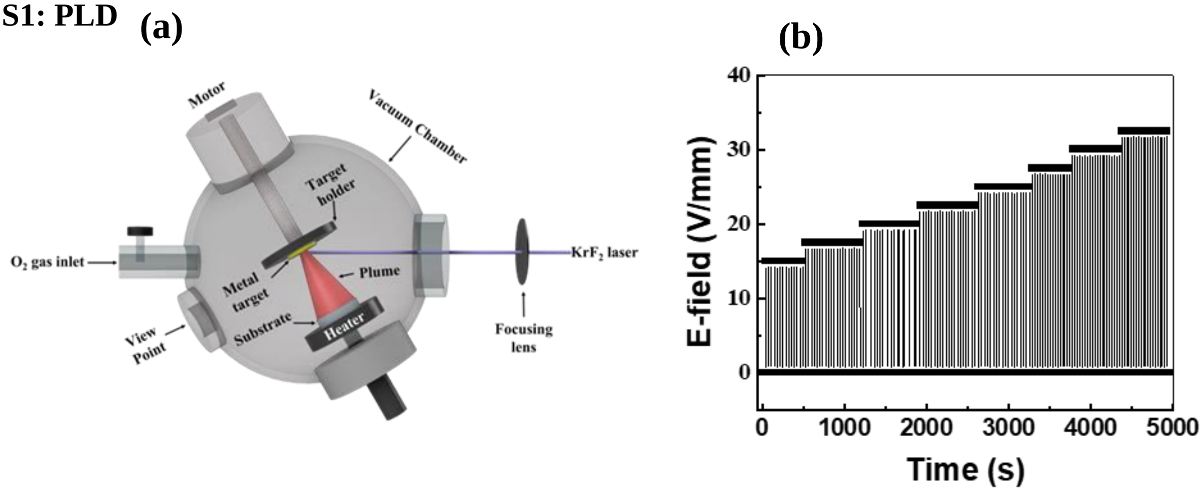

Figure S1:(a) Schematic of the PLD system where nanomechanical resonators were coated by TiO_2 and followed by VO_2 from Titanium and Vanadium metal respectively at oxygen atmosphere, (b) pulsed input signal as a function of time applied across nanomechanical resonator to observe mechanical frequency modulation as shown in Fig 6(a).

S2 Design Parameters for COMSOL Simulation

To simulate and analyze the performance of Micro-string resonator, 3-D model design of the micro-string were made whose dimension is $400 \times 3 \times 0.24\ \mu m\ (L \times w \times t)$. This design was used for analyzing resonance frequency shift as a function of temperature. The material properties that were used are given in table (S-1). In the table there are certain properties that are variable such as Elastic modulus that varies with temperature. All the variations in frequency shift with temperature were analyzed in fundamental mode. The module of FEM calculations utilized in this case was Solid Mechanics with physics involving study of Eigen frequency shift and thermo-elastic expansion of materials. The parametric sweep of temperature ranging from 20-100^{o}C was done to evaluate resonance frequencies corresponding to different temperatures. Along with this added mass corresponding to micro-string (VO_2 and TiO_2) was applied in the form of uniformly distributed Load (UDL).

Table S-1: Input dimension and material properties of microstrings used for simulating the effects of temperature on resonance frequency of VO_2/TiO_2 coated microstring.

S.No.	parameters	Value	Description
1.	L	$4e^{-4}$ m	Reference length (x)
2.	W	$3e^{-6}$ m	Reference length (y)
3.	T	$2.4e^{-7}$ m	Reference length (z)
4.	Rho (ρ)	3170 kgm^{-3}	reference mass density
5.	Nu_o (υ)	0.2	Poisson's ratio
6.	α_x	$1e^{-6}$ 1/K	CTE. X-direction
7.	α_y	$2e^{-5}$ 1/K	CTE. Y-direction
8.	α_z	$3e^{-6}$ 1/K	CTE. Z-direction
9.	dT	20 K	Initial Temperature Shift

As the temperature of the micro-string increases, there is a thermal expansion across the micro-string in all the three directions. The thermal strain is given by relation: -

$$\varepsilon_{th} = \alpha(T)\left(T - Tr\,e\tilde{f}\right)$$

Since the string is clamped at both the end, strain gets restricted resulting in development of thermal stress. This thermal stress modifies the overall stress distribution in the system affecting the resonance frequency of the micro-string given by the expression: -

$$f_i = \frac{i^2\pi}{2l^2}\sqrt{\frac{EI}{\rho A}}\sqrt{1 + \frac{S'l^2}{i^2EI\pi^2}}$$

Here S' corresponds to overall stress in the micro-string due to tensile stress and thermal load stress. The thermal load exerted by SiNx is the major dominant factor which affects the overall tensile stress exerted on TiO_2/VO_2 film. The thermal load exerted by SiN_x is given by the relation:-

$$Q = mC_p(T - T_{ref}) = k_{SiNx}A\,\frac{(T - T_{ref})}{t}$$

Where, m, C_p, k_{SiNx}, t denotes mass, specific heat capacity, thermal conductivity and thickness of the SiN_x material. Higher thermal conductivity ensures faster conduction of heat through the material whereas higher C_p increases the retention time of the heat in the material. Both these parameters affects the thermal stress developed in the silicon nitride material which intern develops tensile stress on VO_2 material leading to reduction in the resonance frequency.

Furthermore, the added mass of VO_2 on SiN_x further reduces the resonance frequency of the micro-string. The Figure S2 below show few images corresponding to fundamental mode at different temperatures along with their resonance frequencies.

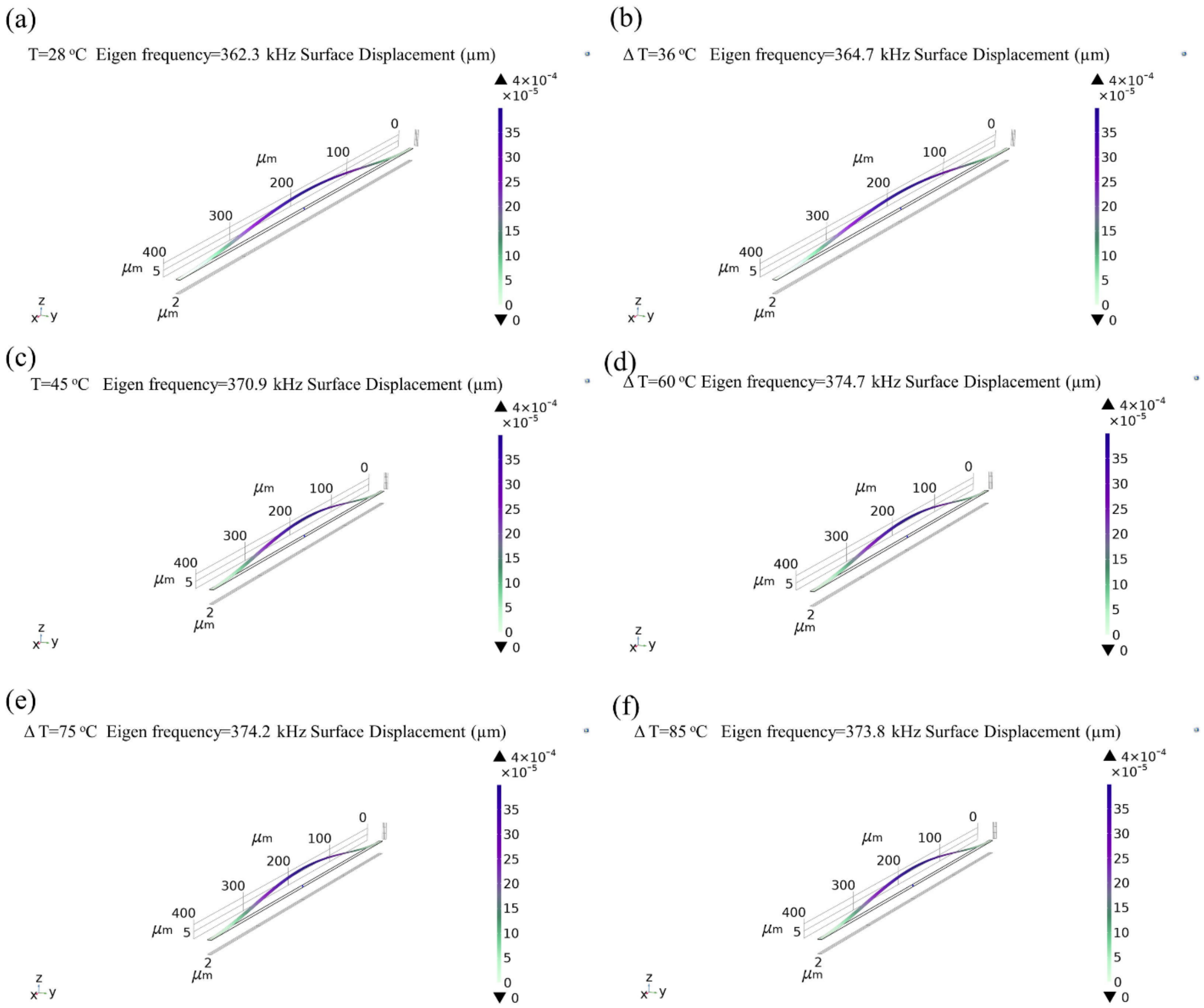

Figure S2. Simulation of fundamental mode frequency at different temperatures.

S3 Simulation of temperature difference variation due to E-field.

In this simulation, Solid mechanics, Heat transfer and Electric current modules were utilized. The Multiphysics combining these modules are thermal expansion, thermoelectric effect, and electromagnetic heating. Here, the thickness of the string was chosen to be 40 nm. This is because E-field is applied across micro-string and the conducting layer is VO_2 and TiO_2

whereas SiN_x is insulating. The properties used in this simulation are summarized in table (S-2).

Table S-2: Input dimension and material properties of microstrings used for simulation.

S.No.	parameters	Value	Description
1.	L_0	$4e^{-4}$ m	Reference length (x)
2.	a_o	$3e^{-6}$ m	Reference length (y)
3.	b_o	$40e^{-9}$ m	Reference length (z)
4.	Rho(ρ)	4600 kgm^{-3}	reference mass density
5.	Nu_o(υ)	0.2	Poisson's ratio
6.	α_x	$1e^{-6}$ 1/K	CTE. X-direction
7.	α_y	$2e^{-5}$ 1/K	CTE. Y-direction
8.	α_y	$3e^{-6}$ 1/K	CTE. Z-direction
9.	L	$2.44e^{-8}$ V^2/K^2	Lorenz number
10.	α	1.6e-6 m^2/s	Thermal diffusivity

Apart from this there are couple of parameters such as electrical conductivity and thermal conductivity, that were derived from experimental data of I-V sweep and resistance (R_T/R_5) vs temperature curve. From I-V sweep which was performed at different temperature, resistance of VO_2 at 5 ^{0}C (R_5) was found to be around 11.1 MΩ. Once the resistance at different temperature were obtained then resistivity of the VO_2 were calculated by the relation $\rho_T = \frac{R_T A}{L_0}$ where A and L_o represent cross sectional area and length of the micro-string. The inverse of resistivity then gives the electrical conductivity of the VO_2 material. The thermal conductivity of the material was finally deduced from the Wiedemann- Franz relation given as: -

$$\frac{k}{\sigma} = LT$$

Here k and σ represents thermal and electrical conductivity of the material, L is the Lorenz number and is a constant parameter equal to 2.44×10^{-8} V^2/K^2.When an Electric field is applied across the micro-string resonator, localized joule heating is generated in the VO_2 string. At lower E-filed, VO_2 is in insulating state and have high resistance. Hence temperature variation due to current flowing through it is less resulting in less drop of temperature. However, with increase in E-field, current increases resulting in large temperature changes and thus bringing VO_2 to its metallic state. The temperature variation across micro-string at different applied E-Field is shown in Figure S3. The careful observation reveals that the node of maximum temperature on the micro-string shifts from one end of the string to the other when the E-field is increased from 2 V/mm to 36 V/mm as shown in Figure S3 (in the supplementary information). At low E-field, the temperature is linearly decreasing across the microstring. This is because when E-field is applied, the end connected to higher potential will be at high temperature as compared to the other end as per Fourier law of heat conduction. However, at the initial state of phase transition i.e. at critical field of 17 V/mm, the thermal conductivity across the micro-strings varies non uniformly resulting in the non-uniform distribution of temperature. In the transition regime, as the monoclinic phase (insulting phase) starts changing to rutile phase (conducting) from one terminal to the other, the maximum temperature of the micro-string shifts accordingly along the microstring as observed in the Figure S3.

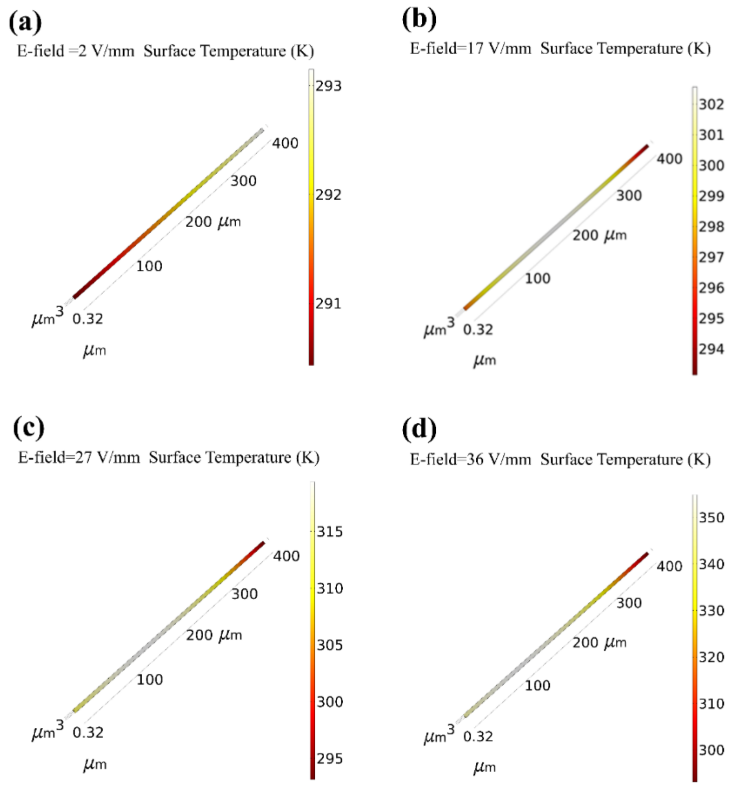

Figure S3. Simulation of surface temperature of micro-string at different applied E-field.

S4 Electrical measurements:

Current vs voltage (electric field) characteristics were performed on the contact pads of the microstring from -10 to 10 V/mm which shows ohmic behavior between VO_2 (semiconductor) and Au (metal) interface as shown in Figure S4.

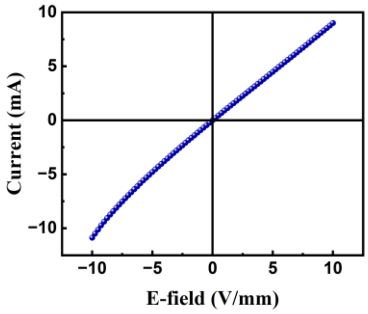

Figure S4. Current vs voltage (electric field) characteristics showing ohmic behaviour on the contacts.