



This is the accepted manuscript made available via CHORUS. The article has been published as:

High-speed sensing of rf signals with phase-change materials

Ranjan Kumar Patel, Yifan Yuan, Ravindra Singh Bisht, Ivan Seskar, Narayan Mandayam,
and Shriram Ramanathan

Phys. Rev. Applied **22**, 014013 — Published 8 July 2024

DOI: [10.1103/PhysRevApplied.22.014013](https://doi.org/10.1103/PhysRevApplied.22.014013)

High-speed sensing of RF signals with phase change materials

Ranjan Kumar Patel,^{1,*} Yifan Yuan,^{1,†} Ravindra Singh Bisht,¹ Ivan Seskar,² Narayan Mandayam,² and Shriram Ramanathan^{1,‡}

¹*Department of Electrical and Computer Engineering, Rutgers University, Piscataway, NJ 08854, USA*

²*WINLAB, Rutgers University, North Brunswick, NJ 08902, USA*

RF radiation spectrum is central to wireless and radar systems among numerous high-frequency device technologies. Here, we demonstrate sensing of RF signals in the technologically relevant 2.4 GHz range utilizing vanadium dioxide (VO_2), a quantum material that has garnered significant interest for its insulator-to-metal transition. We find the electrical resistance of both stoichiometric as well as off-stoichiometric vanadium oxide films can be modulated with RF wave exposures from a distance. The response of the materials to the RF waves can be enhanced by either increasing the power received by the sample or reducing channel separation. We report a significant $\sim 73\%$ drop in resistance with a $5\text{ }\mu\text{m}$ channel gap of the VO_2 film at a characteristic response time of 16 microseconds. The peak sensitivity is proximal to the phase transition temperature boundary that can be engineered via doping and crystal chemistry. Dynamic sensing measurements highlight the films' rapid response and broad-spectrum sensitivity. Engineering electronic phase boundaries in correlated electron systems could offer new capabilities in emerging communication technologies.

INTRODUCTION

Sensing of RF signals and wireless spectrum has increasingly become essential for a wide variety of uses. These range from the classical need for spectrum sensing in cognitive radio (CR) ecosystems to opportunistically use the available spectrum to the more generic uses of RF signals for a variety of applications supported by the Internet of Things (IoT) ecosystems. In CR scenarios, spectrum sensing has been used to create radio maps that allow secondary spectrum users to exploit available spectrum holes and peacefully coexist with primary (incumbent) users of spectrum [1]. In IoT ecosystems, RF signal sensing has been used for a variety of applications, e.g., environmental monitoring, healthcare, advanced manufacturing [2], to name a few. Further, the developments in the evolution of 6G wireless technologies have underscored the importance of sensing by seeking to integrate communications and sensing in a joint framework [3].

The need for RF sensing without necessarily using complex (and often frequency-specific) signal processing is attractive. Further, having such sensing accomplished at high speeds is particularly relevant for not only supporting low latency communications but also for enabling follow-up actions related to possibly network security and control. While the sensing methodology envisioned here is applicable even in the far-field, near-field sensing is becoming increasingly relevant with the emergence of the IoT ecosystem, with high densities of devices in close geographical proximity to each other for various machine-to-machine communications scenarios, including sensors in body and personal area networks. Motivated by the above, we investigate RF sensing utilizing a novel materials-based sensing approach in the near-field that can be used seamlessly in a wide variety of scenarios.

Materials exhibiting electronic phase transitions are well-suited for sensing applications. Vanadium dioxide (VO_2), a prototypical quantum material characterized by its insulator-to-metal transition (IMT) near room temperature, has been explored as switches [4–6] and sensors for chemical, thermal, and terahertz detection [7–10]. The IMT characteristics can

be further modified by utilizing an off-stoichiometric vanadium oxide compound, denoted as VO_x [11–13]. Simultaneously, the V:O materials family is recognized for its efficacy as a bolometer [14–16], exemplifying the versatile applications of such materials in sensing technologies. Here, we demonstrated the effect of RF waves on VO_2 and off-stoichiometric VO_x films on $c\text{-Al}_2\text{O}_3$ (0001) substrate by varying different parameters, such as the temperature, frequency, device geometry, distance of the film from the RF antenna, gain and power of the RF waves. We particularly focus on the 2.4 GHz frequency range due to its importance in wireless communications. Our findings suggest that the studied materials can be promising candidates for RF sensors, potentially contributing to advancements in future Wi-Fi technologies.

EXPERIMENTAL DETAILS

VO_2 and off-stoichiometric VO_x films of thickness $\sim 40\text{ nm}$ were grown on c -axis (0001) sapphire (Al_2O_3) substrates by a radio-frequency (RF) magnetron sputtering (AJA International) system [11]. A ceramic V_2O_5 target of 99.9 % purity was used with 100 W RF power. The V_2O_5 target was pre-sputtered for 5 minutes before the deposition. During deposition, the pressure was maintained at 5 mTorr by introducing 49.5 SCCM (standard cubic centimeters per minute) Ar and 0.5 SCCM O_2 -Ar (10%-90%) mix gases for VO_2 growth, whereas 49.9 SCCM Ar and 0.1 SCCM O_2 gases were used for VO_x growth. The substrate temperature was 650°C , and the substrate holder was rotated at 40 rpm during the growth to maintain the homogeneity of the sample. Post deposition, the substrate was cooled down to room temperature at the growth pressure. Pt and Ni electrodes were deposited (using sputtering) at room temperature on VO_2 and VO_x films using a shadow mask, respectively. This was carried out to facilitate electrical measurements across millimeter-scale junctions, with a channel separation of $300\text{ }\mu\text{m}$, $900\text{ }\mu\text{m}$, $2100\text{ }\mu\text{m}$, and $4500\text{ }\mu\text{m}$ (and a channel width of $300\text{ }\mu\text{m}$). To investigate micro-scale junctions, VO_2 devices with $5\text{ }\mu\text{m}$, $15\text{ }\mu\text{m}$,

25 μm , and 30 μm separation between the electrodes (and a channel width of 5 μm) were fabricated through photolithography using a photoresist of AZ 1518 as the masking layer for the process. Heidelberg MLA150 Maskless Aligner was used to write the electrode pattern [17]. A 100-nanometer thick layer of Pt was deposited through e-beam evaporation and subsequently lifted off by using PG-Remover at 80°C.

The X-ray diffraction (XRD) patterns of the substrate and as-deposited films were recorded by using a lab-based Panalytical Xpert diffractometer with a Cu source. Rutherford backscattering spectroscopy (RBS) measurements were performed to estimate the stoichiometry by using a 1.7 MV IONEX tandem accelerator with a 2.3 MeV He^{2+} ion beam of diameter 2 mm. The scattering angle of the detector was 163 degrees, and the resolution of the detector was 18 keV. The RBS data were analyzed by using the SIMNRA program [18]. The *dc* transport measurements were performed on a probe station by using a Keithley 2635A source meter, and the temperature was controlled by using a Quiet CHUCK DC Hot Chuck system (see Fig. 1(f) and Fig. S1 of Supplementary Materials [19] for experimental setup). The electrical contacts were made by contacting the micromanipulator tips of the probe station to the metal electrodes directly. The resistance was measured by taking the slope of the *IV* data taken between -0.05 V and +0.05 V in a two-probe configuration. The time-resolved measurements were performed by using a Keithley 2461 source meter by applying a constant voltage of +0.05 V.

In the RF measurement setup, an X86-based Software Defined Radio (SDR) platform (Quad-core i7 embedded PC) was used and equipped with a B210 USRP (Universal Software Radio Peripheral) and a directional antenna. The USRP, interfaced with the SDR platform, utilized User Hardware Driver (UHD) tools for the precise generation and control of RF waveforms. To augment the system, it was connected to the output of the USRP, significantly enhancing the emitted RF signal strength. This setup was instrumental in effectively exciting VO_2 and VO_x films on *c*- Al_2O_3 substrates. The waveform used was a narrow band sine wave, with the gain values listed in the paper corresponding to the UHD tx_waveform utility command line gain argument. The directional antenna, in conjunction with the amplified signal from the power amplifier, focused the RF energy onto the samples in the lab, as shown in Fig. 1(f) and Fig. S1 of Supplementary Materials [19]. The software-based waveform configuration enabled precise control over key parameters, such as frequency and power. We calibrated our setup with a spectrum analyzer in the COSMOS testbed environment at WINLAB [20], measuring the received power by the films at various distances from the SDR setup and with different gain values (see Fig. S2 of Supplementary Materials [19] for the calibration setup). All the measurements were done in the near-field regime. The 'near field' context in our experiment is defined by the close proximity between the antenna and the device, where the electromagnetic interactions are governed by near-field principles, including considerations of the first Fresnel zone,

rather than the propagation-dominated interactions typical of far-field contexts.

RESULTS AND DISCUSSION

In order to check the structural quality of the VO_2 and VO_x films grown on sapphire substrate by RF sputtering, we have recorded 2θ - ω diffraction scan [Fig. 1(a)]. For comparison, the XRD pattern of the single crystal sapphire substrate was also measured and shown in Fig. 1(a). The XRD scan of the VO_2 and VO_x films consists of a broader film peak (marked by *) and a sharp substrate peak ($2\theta = 41.68^\circ$) [21], where the substrate peak arises due to the (0006) reflection of the *c*- Al_2O_3 . For the VO_2 film, a well-defined XRD peak corresponding to the monoclinic (020) phase [21] was observed at $2\theta = 39.86^\circ$. From this data, the lattice distance was estimated ($b_m = 4.52 \text{ \AA}$), which is similar to the respective literature value of expected monoclinic VO_2 [22]. For the off-stoichiometric sample (VO_x), the XRD peak was observed at $2\theta = 40.08^\circ$, which indicates a value of $b_m = 4.5 \text{ \AA}$. This slight shift of the XRD peak is related to the oxygen non-stoichiometry in the VO_x film [23, 24]. Apart from this peak shift, no new diffraction peaks are observed. Additionally, to estimate the elemental composition, we performed Rutherford backscattering spectroscopy (RBS) experiments. In RBS, the qualitative determination of the areal density of the elements is possible by analyzing the intensity and energy of the backscattered He^{2+} ions from the sample within 1-2% accuracy [25]. Figures 1(b)-(c) show the RBS analysis data of VO_2 and VO_x films, respectively, and the values obtained from the analysis are summarized in Table I. For VO_2 and VO_x films, the ratio of the spatially averaged areal density of vanadium to oxygen (V:O) are estimated as 1:2 and 1:1.7, respectively.

Following the structural measurements, we have investigated the electrical transport properties of the films. As reported earlier [11, 21, 22, 26, 27], VO_2 film on Al_2O_3 substrate undergoes an insulator-to-metal transition (IMT) accompanied by a structural change from monoclinic to tetragonal rutile structure upon increasing the temperature. Figure 1(d) shows the temperature-dependent resistance of VO_2 and VO_x films on *c*- Al_2O_3 substrate. For the stoichiometric VO_2 sample, the resistance changes abruptly around four orders of magnitude, which verifies the high quality of the film. On the other hand, VO_x film undergoes a resistance change of around two orders of magnitude. This is characteristic of oxygen-deficient vanadium oxides that show suppressed insulating state resistance and transition temperature. The IMT temperature was calculated by plotting the $d(\ln R)/dT$ as a function of temperature and taking the maximum magnitude after fitting with a Gaussian curve [Fig. 1(e)]. The IMT of the VO_2 in heating ($T_{\text{IMT}}^h \sim 70.6^\circ\text{C}$) and cooling runs ($T_{\text{IMT}}^c \sim 64.1^\circ\text{C}$) are higher compared to the bulk VO_2 ($T_{\text{IMT}}^h \sim 68^\circ\text{C}$) and is related to the tensile strain [22, 28, 29]. Again, for the off-stoichiometric VO_x sample, T_{IMT}^h and T_{IMT}^c are calculated as 64.3°C and 59.4°C , respectively, which are lesser

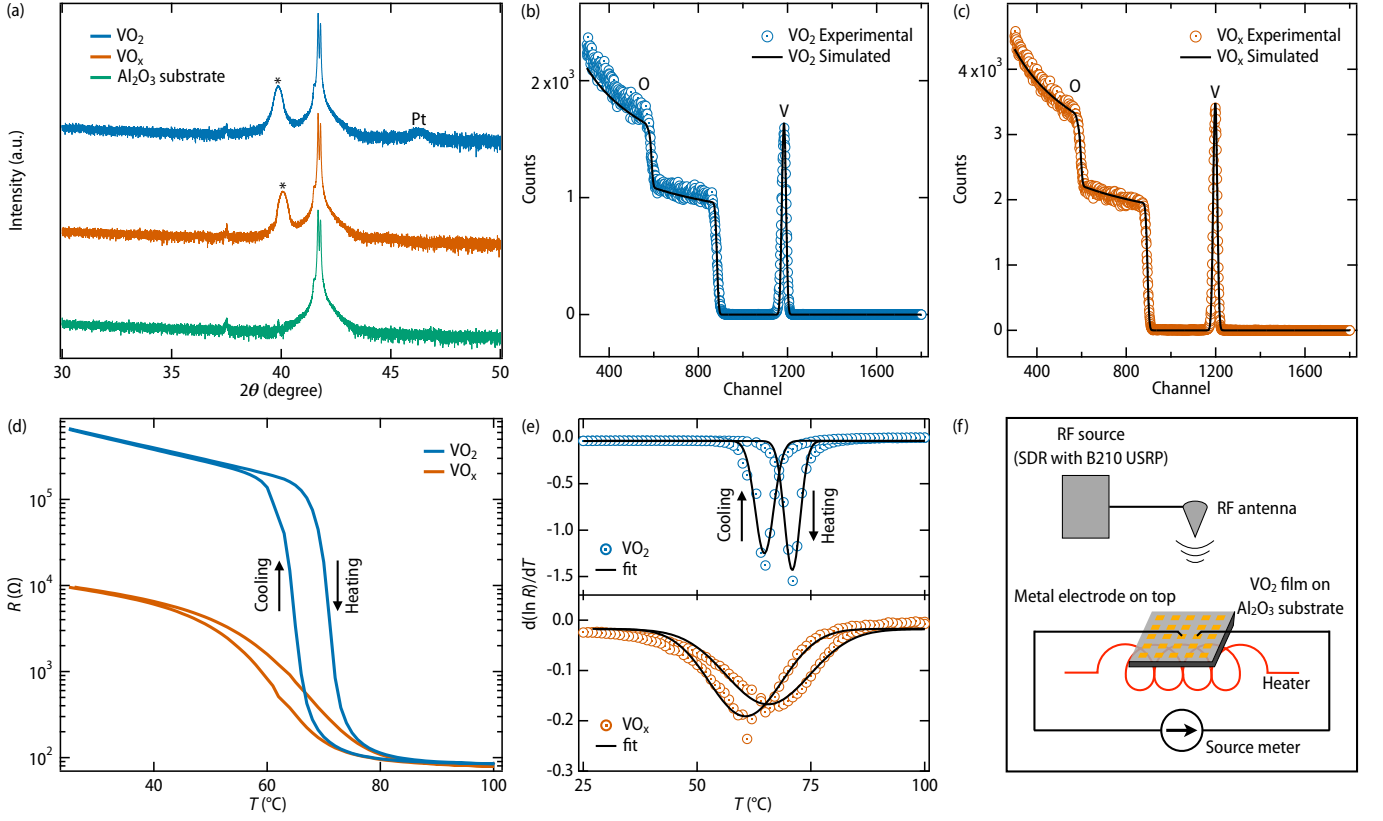


FIG. 1. (a) 2θ - ω XRD scan for VO₂ and VO_x films. (b)-(c) Experimental and simulated Rutherford backscattering spectroscopy data for VO₂ and VO_x films, respectively. (d) Resistance as a function of temperature of the VO₂ and VO_x films. (e) Gaussian fitting of the differential curves of resistance vs. temperature to extract the IMT for the VO₂ and VO_x films. (f) A schematic representation of the experimental setup for electrical and RF radiation measurements.

TABLE I. Summary of RBS and transport data

sample	V ($\times 10^{15}$ atoms/cm ²)	O ($\times 10^{15}$ atoms/cm ²)	T_{IMT}^h (°C)	T_{IMT}^c (°C)
VO ₂	101.9	204.1	70.6	64.1
VO _x	103.6	176.4	64.3	59.4

compared to the stoichiometric VO₂ sample.

After probing the structural and electronic properties of the stoichiometric and off-stoichiometric samples, we delved into the impact of radio frequency (RF) wave exposure on these films. The upper panels of Figs. 2(a)-(b) show the on/off-state of the RF signal. The samples were heated to the desired temperature for each measurement. Once the temperature stabilized, the system was driven out of equilibrium by concentrating a 2.4 GHz RF wave with 100 gain from a distance of 8 cm onto the samples for 5 minutes during the on-state. Following each set of sensing measurements at a specific temperature, the films were ramped to 100°C to remove any persistent conductivity or history effects. Subsequently, the samples were cooled down to room temperature and then heated to the desired temperature for the next measurement. Figures 2(a)-(b) show the relative percentage change in resistance (RPCR),

calculated using the formula $((R-R_0)/R_0)*100$ (R_0 is the initial resistance when the RF signal was turned off) as a function of time at different temperatures of the VO₂ and VO_x samples, respectively. Firstly, a drop in resistance was observed as soon as the RF signal was activated, making the material more conducting. It is worth noting that the RF wave with a frequency of 2.4 GHz corresponds to a energy of 9.93 μeV , which is not sufficient for the excitation of electrons from the valence band to the conduction band as the band gap of VO₂ is around 0.7 eV [26]. Therefore, this decrease in resistance induced by the RF wave may be due to the selective excitation of trapped electrons to the conduction band. Prior studies have demonstrated an IMT phase transition in VO₂ coplanar waveguides induced by intense high frequency radiation [30, 31]. The decrease in resistance caused by RF waves may also occur due to alternative mechanisms, such as influencing the formation

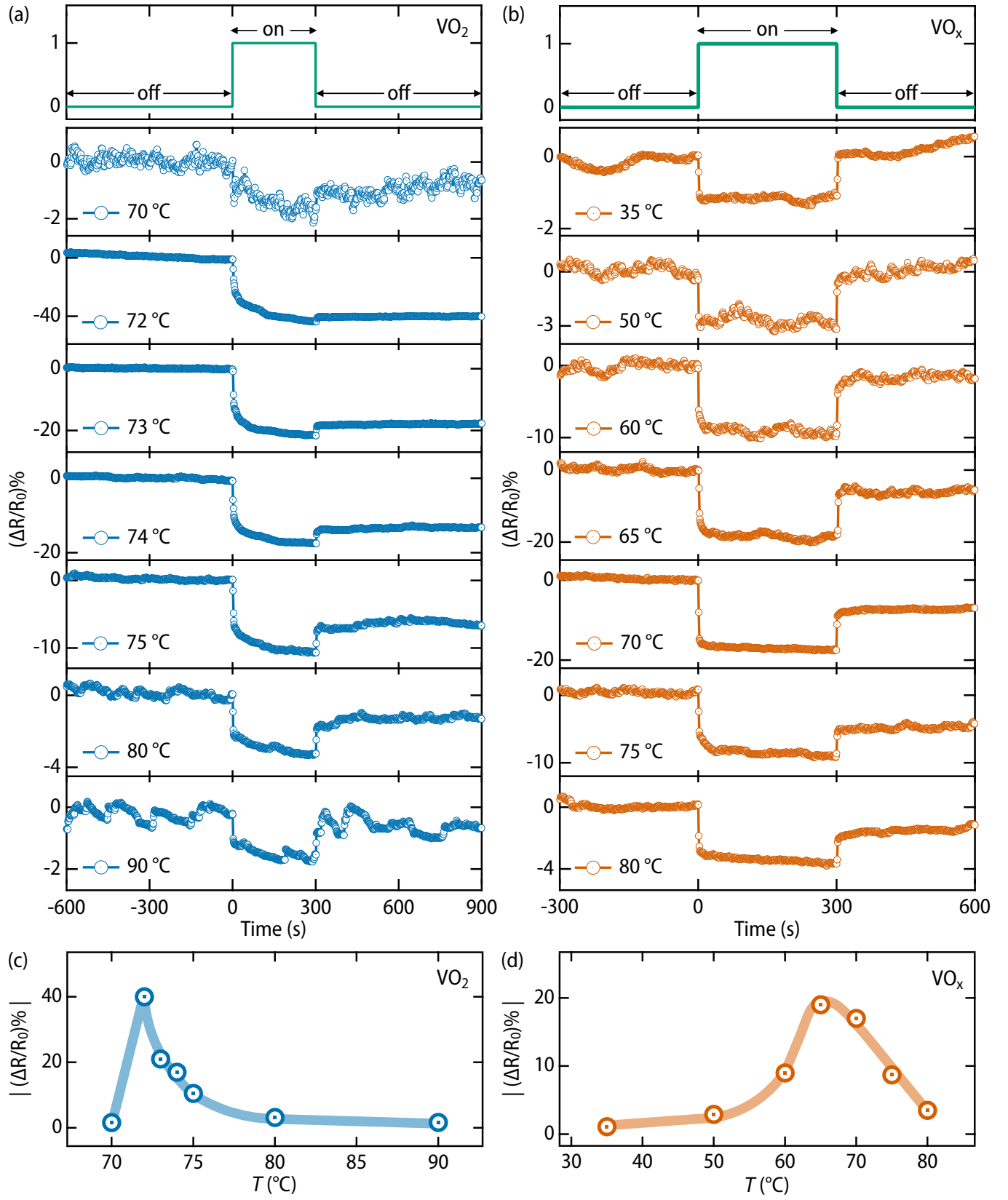


FIG. 2. (a)-(b) Relative percentage change in resistance under irradiation of RF signal (2.4 GHz with 100 gain for 5 min at 8 cm distance) at different temperatures of the VO_2 and VO_x films, respectively. The top panels of (a) and (b) show the schematics representing the on/off-state of the RF signal with time. (c)-(d) Temporal evolution of the maximum relative percentage change in resistance of the VO_2 and VO_x films, respectively.

of conductive filaments within the VO_2 film [9, 10, 32, 33] or through the liberation of Poole-Frenkel electrons, where the electric field reduces the potential barrier, leading to a slight elevation in the carrier density [30, 34]. Moreover, the reduction in the RPCR due to the influence of RF waves can be anticipated through a straightforward application of the Joule heating mechanism [30, 35]. In this latter scenario, RF waves locally heat the film, causing a small temperature rise and subsequently making the sample more conductive. However, we measured the resistance versus temperature of the VO_2 film with the RF radiation both on and off (see Fig. S3 of Supplementary Materials [19]). The two curves can not be overlapped by simply shifting them along the temperature axis. Further, the change in temperature due to RF radiation is estimated at different temperatures from the RT curve [Fig. 1(c)] and RPCR [Fig. 2(a)] of the VO_2 film as discussed in section S4 of the Supplementary Materials [19]. These observations suggest a non-thermal effect associated with the RF radiation on the VO_2 film.

Secondly, there is a sharp increase in the resistance of the VO_2 film immediately after the RF signal is turned off, which again suggests a different mechanism potentially distinct from only Joule heating, as the resistance typically recovers gradually in the case of heat dissipation [36, 37]. To check whether this resistance change with the RF signal is related to the material's structure, we conducted X-ray diffraction (XRD) measurements after shining 2.4 GHz RF waves on a VO_2 sample for 5 minutes. However, there was no observable change in the film peak (see Fig. S5 of Supplementary Materials [19]). Thirdly, when the samples were in either the insulating or metallic state, the resistance recovered back to the original resistance (R_0), whereas the resistance did not fully recover to the original value after removing the RF signal when the samples were in the hysteresis region. This behavior can be well explained by the hysteresis effect, where the resistance does not return to its initial value if the temperature is ramped up (down) and down (up) only within the hysteresis region [38, 39]. The abrupt change of channel resistance with RF waves at different temperatures is fascinating as this can be exploited as a design parameter in sensing. Figures 2(c)-(d) illustrate the RPCR as a function of measured temperatures for the VO_2 and VO_x samples, respectively. Interestingly, the maxima of the curves intriguingly close to the T_{IMT}^h , which suggests maximum changes in resistance approaching the percolation threshold [40–42]. In future, in-operando microscopy techniques such as scanning microwave impedance microscopy (SMIM) and scanning near-field infrared microscopy (SNIM) coupled with RF exposure could enable a comprehensive understanding of the microscopic mechanisms involved and could form the subject of further studies.

To check the reproducibility, a 2.4 GHz RF wave with 100 gain was concentrated on a VO_x sample for 5 minutes from a distance of 8 cm at 73°C. This procedure was then repeated for the same sample and also for a different sample (see Fig. S6 of Supplementary Materials [19]). The RPCR for all these

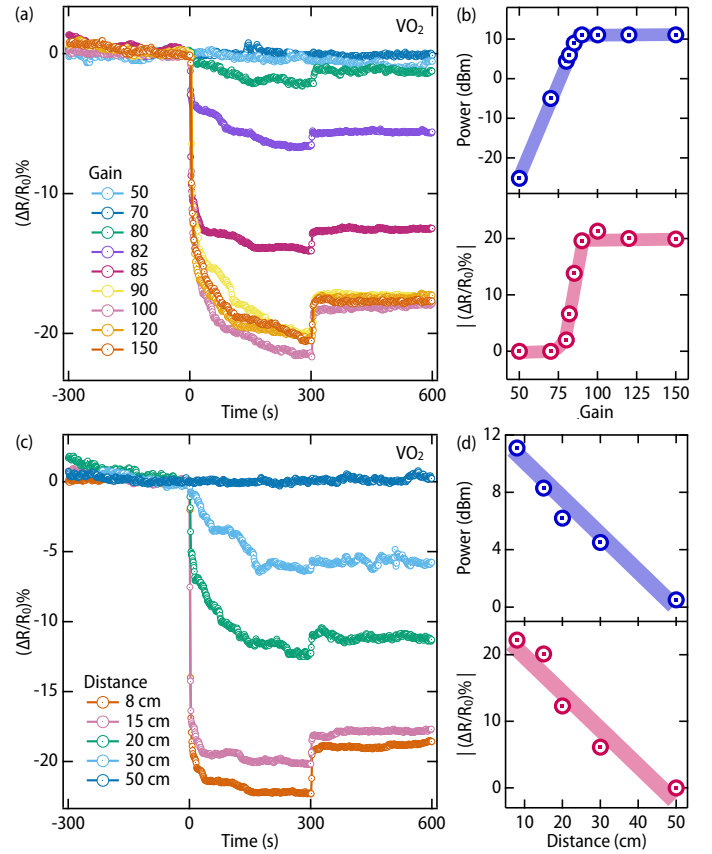


FIG. 3. (a) Relative percentage change in resistance (RPCR) under RF signal (2.4 GHz at 73°C for 5 min at 8 cm distance) at different gain values of the VO_2 film. (b) The power received and the maximum relative percentage change in resistance change with the gain. (c) RPCR of the VO_2 film under RF signal (2.4 GHz with a gain of 100 at 73°C for 5 min) from different distances. (d) The power received and the maximum relative percentage change in resistance change with distances from the RF antenna.

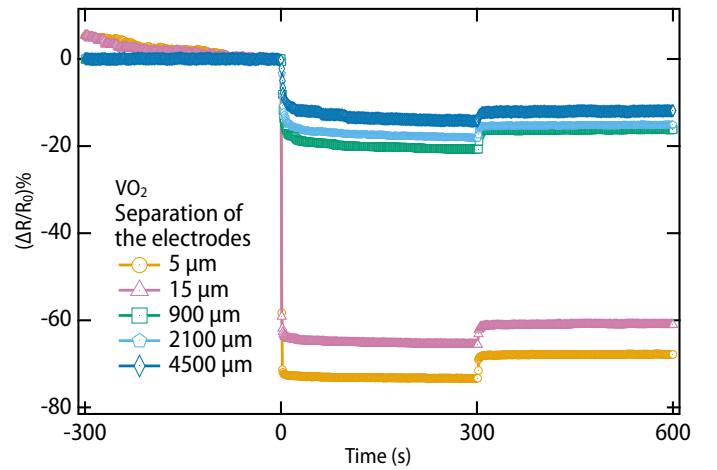


FIG. 4. Relative percentage change in resistance with a 2.4 GHz RF signal (with a gain of 100 at 73°C for 5 min at a distance of 8 cm) of VO_2 films with different separations of electrodes.

TABLE II. Peak RPCR as a function of electrode separation

electrode separation	5 μm	15 μm	300 μm	900 μm	2100 μm	4500 μm
Peak RPCR	73.29	65.48	21.23	20.55	17.74	13.93

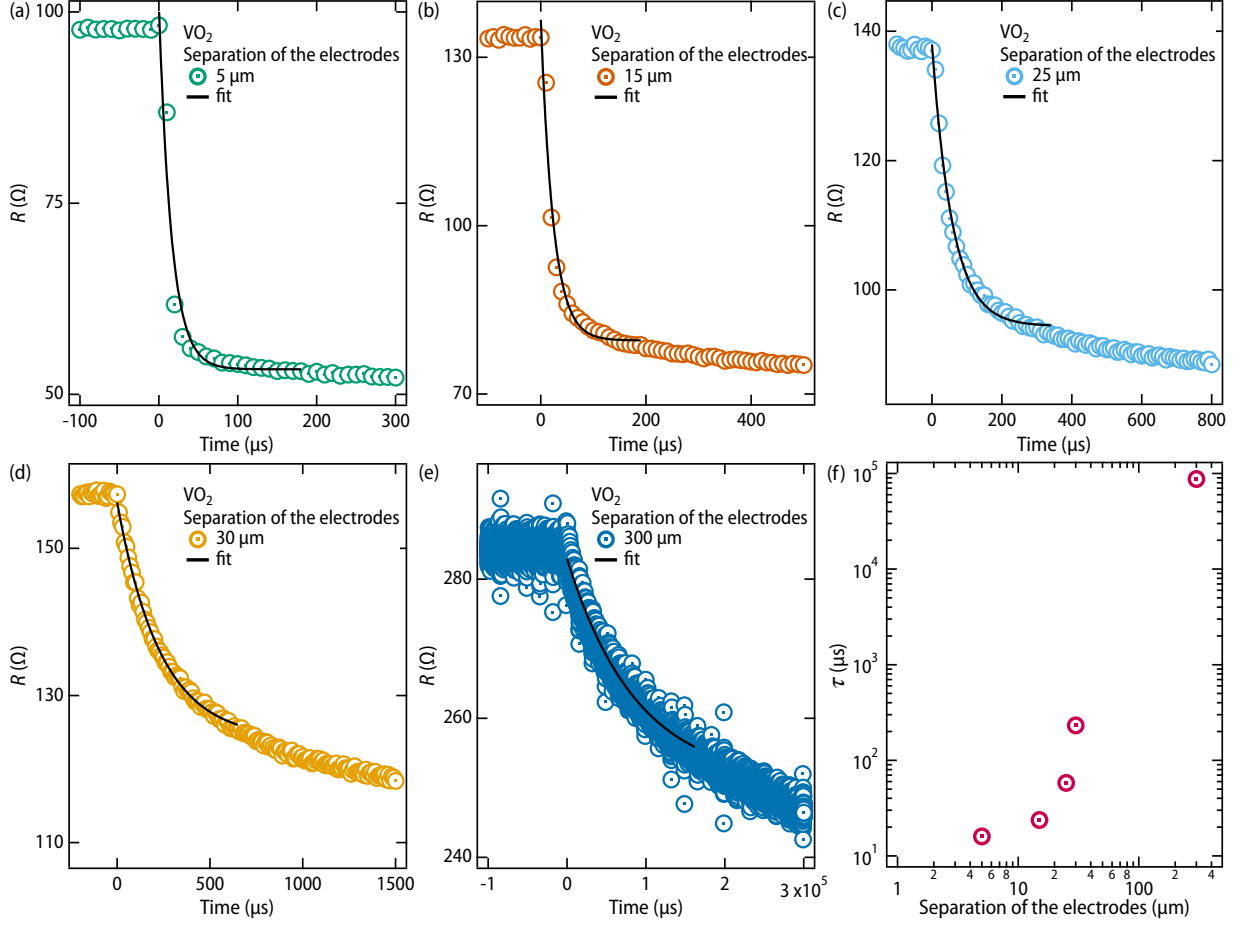


FIG. 5. (a)-(e) Resistance as a function of time in microsecond time scale with a 2.4 GHz RF signal (with a gain of 100 at 73°C at a distance of 8 cm) of VO₂ films with different separations of electrodes. The black curves are the exponential fit to the data to extract the time constant. (f) Time constant as a function of the separation of the electrodes of the VO₂ film.

cases are found to be almost identical. Additionally, we explored the influence of RF waves on the sample using frequencies other than the technologically important 2.4 GHz used in wireless communications such as Wi-Fi and cellular applications. We observed similar conductance modulation effects on the VO₂ film (see Fig. S7 of Supplementary Materials [19]), suggesting that the conductance modulation phenomenon is not exclusive to specific frequencies but holds true across a range of RF waves. This versatility in responsiveness to diverse frequencies positions VO₂ as a potential candidate for applications in the evolving landscape of communication technologies.

After establishing the effect of RF waves on VO₂ and VO_x samples at different temperatures, we explored the effect of RF signal strength by varying the power. Figure 3(a) shows

the RPCR of the VO₂ sample as a function of time when radiated with a 2.4 GHz RF signal (for 5 minutes at a distance of 8 cm) at 73°C with different gain values. The power received at the sample surface corresponding to the gain and the maximum relative percentage change in resistance with gain is shown in Fig. 3(b). Notably, the maximum RPCR remains minimal at lower gains (50 and 60), increases progressively with higher gain values, and stabilizes when the gain exceeds 80. It's worth noting that the RPCR is directly proportional to the power received by the sample at a constant temperature. Furthermore, Fig. 3(c) shows the RPCR as a function of time, while the RF wave was concentrated on the VO₂ film from different distances between the RF antenna and the sample. As can be seen from the graph, the RPCR decreases with increasing distance between the RF source and the sample. This can

be understood by considering the decrease of power with increasing distance. To validate this, we measured the power at the corresponding distances and found that the power indeed decreases as the distance increases [Fig. 3(d)]. Therefore, the observed changes in RPCR concerning gain and distance can be attributed to the power received by the sample.

Next, we examined the effect of RF waves on sensor channel dimensions by varying the spacing between the metal electrodes on the VO₂ sample. Figure 4 shows that an increase in the distance between the electrodes (or sample size) results in a decrease in the RPCR when a 2.4 GHz RF wave with a gain value of 100 from a distance of 8 cm was turned on at a sample temperature of 73°C. All the measurements were done using a probing voltage of ± 0.05 V, which may be high enough to induce conducting filament formation in VO₂ devices, especially when the temperature is close to the phase transition [32, 43].

Therefore, we also measured the RPCR of the 15 μ m VO₂ device at 73°C using smaller voltages (± 0.005 V and ± 0.0005 V) under a 2.4 GHz RF radiation with a gain of 100 from a distance of 8 cm (see Fig. S8 of Supplementary Materials [19]). Also, we repeated the RPCR measurement of the VO₂ film with different gain values that has been measured before [in Fig. 3(a)] by using a smaller voltage of ± 0.0005 V (see Fig. S9 of the Supplementary Materials [19]). A similar value of RPCR obtained by applying smaller voltages suggests that the change in RPCR of VO₂ film is due to the RF radiation and not because of the higher probed current/voltages. Further, we used a VO₂ film with much smaller electrode separations to enhance the RPCR. The relative percentage change in the resistance were found to be ~ 73 % and 65 %, when the electrode separations were 5 μ m and 15 μ m, respectively. The values of peak RPCR as a function of electrode separation are shown in Table II. The enhancement in sensitivity by reducing the channel separation points towards further opportunities for the optimization of sensors for practical technologies.

To elucidate the dynamics associated with the reduction in resistance induced by RF waves, we conducted time-resolved measurements, capturing resistance values at intervals of 10 microseconds. Figures 5(a)-(e) show the temporal evolution of resistance drop upon the activation of RF waves, focusing on various channel separations within the VO₂ film (see Fig. S10 of Supplementary Materials [19] for the evolution of resistance for a longer time scale). It is noteworthy to highlight that the response time scales varies with channel dimensions. The drop in resistance exhibits a distinct profile, characterized by a sharp and rapid reduction in the case of shorter channels, transitioning to a more gradual descent as the channel separation is increased. To understand the time constant related to the drop of the resistance with RF wave, we fitted the resistance (R) vs. time (t) curve (immediately following the RF exposure) with the equation, $R = a + be^{-t/\tau}$, where a , b are constants and τ is the time constant [black curves in Figs. 5(a)-(e)]. The time constant increases with the increase of the channel separation of the VO₂ film [Fig. 5(f)]. This insight points towards the intricate interplay between channel dimensions

and the manifestation of RF-induced effects, particularly in the context of conducting filament formation within the VO₂ film that has previously been ascribed as a possible mechanism for reduction in resistance of the vanadium oxide films exposed to THz fields [9, 10]. The high speed response could potentially be enhanced further by reducing channel separation through the application of advanced techniques such as e-beam lithography or other similar methods.

CONCLUSIONS

To summarize, we have grown VO₂ and off-stoichiometric VO_x films on *c*-Al₂O₃ substrates and studied their structural and electrical properties by XRD, RBS, and transport measurements. Further, we have investigated the effect of 2.4 GHz radiation on these samples by varying the temperature, frequency, gain, distance, power, and sample size. Interestingly, the application of the RF wave makes the samples more conducting and opens up avenues for applications as RF sensors. The relative percentage change in resistance scales with decreasing channel separation, reaching a value of ~ 73 % for the 5 μ m channel gap. We found that the samples are most sensitive proximal to the transition boundary, and this offers a path to devices that can respond at various temperatures by varying crystal stoichiometry and doping. The time-resolved RF measurements suggest the rapid response of the film in microsecond time scales upon the incidence of RF waves. Furthermore, the influence of RF waves is detectable across a broad spectrum of microwave frequencies, offering potential applications in future communications technologies.

ACKNOWLEDGEMENT

The authors acknowledge Analytical Characterization Laboratories and Laboratory for Surface Modification Facilities at Rutgers University for XRD and RBS measurements, respectively. We acknowledge Haoming Yu for the fabrication through photolithography of the VO₂ sample. We are grateful to Prof. Michael Gershenson and Plamen Kamenov for the use of the sputtering system. We acknowledge Air Force Office of Scientific Research AFOSR FA9550-23-1-0215 that supported the film growth.

* Contributed equally; ranjan.patel@rutgers.edu

† Contributed equally

‡ shriram.ramanathan@rutgers.edu

- [1] I. F. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty, Next generation/dynamic spectrum access/cognitive radio wireless networks: A survey, *Computer Networks* **50**, 2127 (2006).
- [2] L. Lubna, H. Hameed, S. Ansari, A. Zahid, A. Sharif, H. T. Abbas, F. Alqahtani, N. Mufti, S. Ullah, M. A. Imran, and Q. H. Abbasi, Radio frequency sensing and its innovative applications

- in diverse sectors: A comprehensive study, *Frontiers in Communications and Networks* **3**, 10.3389/frcmn.2022.1010228 (2022).
- [3] D. K. Pin Tan, J. He, Y. Li, A. Bayesteh, Y. Chen, P. Zhu, and W. Tong, Integrated Sensing and Communication in 6G: Motivations, Use Cases, Requirements, Challenges and Future Directions, in *2021 1st IEEE International Online Symposium on Joint Communications & Sensing* (2021) pp. 1–6.
 - [4] B.-G. Chae, H.-T. Kim, D.-H. Youn, and K.-Y. Kang, Abrupt metal–insulator transition observed in VO₂ thin films induced by a switching voltage pulse, *Physica B: Condensed Matter* **369**, 76 (2005).
 - [5] D. E. Anagnostou, D. Torres, T. S. Teeslink, and N. Sepulveda, Vanadium Dioxide for Reconfigurable Antennas and Microwave Devices: Enabling RF Reconfigurability Through Smart Materials, *IEEE Antennas and Propagation Magazine* **62**, 58 (2020).
 - [6] N. Ghazikhanian, J. del Valle, P. Salev, R. El Hage, Y. Kalcheim, C. Adda, and I. K. Schuller, Resistive switching localization by selective focused ion beam irradiation, *Applied Physics Letters* **123**, 123505 (2023), <https://pubs.aip.org/aip/apl/article-pdf/doi/10.1063/5.0151823/18131881/123505.1.5.0151823.pdf>.
 - [7] B.-J. Kim, Y. W. Lee, B.-G. Chae, S. J. Yun, S.-Y. Oh, H.-T. Kim, and Y.-S. Lim, Temperature dependence of the first-order metal–insulator transition in VO₂ and programmable critical temperature sensor, *Applied Physics Letters* **90**, 023515 (2007), <https://pubs.aip.org/aip/apl/article-pdf/doi/10.1063/1.2431456/14025954/023515.1.online.pdf>.
 - [8] E. Strelcov, Y. Lilach, and A. Kolmakov, Gas Sensor Based on Metal–Insulator Transition in VO₂ Nanowire Thermistor, *Nano Letters* **9**, 2322 (2009).
 - [9] F. Qaderi, T. Rosca, M. Burla, J. Leuthold, D. Flandre, and A. M. Ionescu, Millimeter-wave to near-terahertz sensors based on reversible insulator-to-metal transition in VO₂, *Communications Materials* **4**, 34 (2023).
 - [10] F. Qaderi, Y. Horst, T. Blatter, M. Burla, D. Park, A. Gilani, J. Leuthold, and A. M. Ionescu, Subthreshold VO₂ vertical switches for large-bandwidth millimeter-wave and sub-terahertz detection, in *2022 47th International Conference on Infrared, Millimeter and Terahertz Waves (IRMMW-THz)* (2022) pp. 1–2.
 - [11] Z. Zhang, F. Zuo, C. Wan, A. Dutta, J. Kim, J. Rensberg, R. Nawrodt, H. H. Park, T. J. Larrabee, X. Guan, Y. Zhou, S. M. Prokes, C. Ronning, V. M. Shalae, A. Boltasseva, M. A. Kats, and S. Ramanathan, Evolution of Metallicity in Vanadium Dioxide by Creation of Oxygen Vacancies, *Phys. Rev. Appl.* **7**, 034008 (2017).
 - [12] J. Zhang, Z. Zhao, J. Li, H. Jin, F. Rehman, P. Chen, Y. Jiang, C. Chen, M. Cao, and Y. Zhao, Evolution of Structural and Electrical Properties of Oxygen-Deficient VO₂ under Low Temperature Heating Process, *ACS Applied Materials & Interfaces* **9**, 27135 (2017).
 - [13] J. G. Ramirez, T. Saerbeck, S. Wang, J. Trastoy, M. Malnou, J. Lesueur, J.-P. Crocombette, J. E. Villegas, and I. K. Schuller, Effect of disorder on the metal–insulator transition of vanadium oxides: Local versus global effects, *Phys. Rev. B* **91**, 205123 (2015).
 - [14] B. Wang, J. Lai, E. Zhao, H. Hu, and S. Chen, Research on VO_x uncooled infrared bolometer based on porous silicon, *Frontiers of Optoelectronics* **5**, 292 (2012).
 - [15] D. Wang, J. Bae, H.-J. Choi, S.-H. Baek, S. Woo, D. Park, and W. J. Choi, Modification of electrical properties of amorphous vanadium oxide (a-VO_x) thin film thermistor for microbolometer, *Journal of Alloys and Compounds* **937**, 168295 (2023).
 - [16] B. Wang, N. Li, W.-F. Xie, J.-J. Lai, S.-Y. Wang, Y. Zheng, Z.-T. Chi, B. Yu, Y.-Q. Shen, and H.-L. Cong, Fabrication and characteristics of VO_x microbolometer integrated into gold black absorbing layer, *Ferroelectrics* **579**, 70 (2021).
 - [17] S. Deng, H. Yu, T. J. Park, A. N. Islam, S. Manna, A. Pofelski, Q. Wang, Y. Zhu, S. K. Sankaranarayanan, A. Sengupta, and S. Ramanathan, Selective area doping for Mott neuromorphic electronics, *Science Advances* **9**, eade4838 (2023), <https://www.science.org/doi/pdf/10.1126/sciadv.ade4838>.
 - [18] M. Mayer, Ion beam analysis of rough thin films, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* **194**, 177 (2002).
 - [19] See Supplementary Materials for experimental setup in the lab, calibration setup in the WINLAB, the effect of RF radiation on structural and transport properties, estimation of temperature change with RF radiation, reproducibility data, the effect of different RF frequencies on resistance, a similar RPCR using smaller voltages, and time-resolved measurements of the devices.
 - [20] D. Raychaudhuri, I. Seskar, G. Zussman, T. Korakis, D. Kilper, T. Chen, J. Kolodziejewski, M. Sherman, Z. Kostic, X. Gu, H. Krishnaswamy, S. Maheshwari, P. Skrimponis, and C. Gutterman, Challenge: COSMOS: A City-Scale Programmable Testbed for Experimentation with Advanced Wireless, in *Proceedings of the 26th Annual International Conference on Mobile Computing and Networking*, MobiCom '20 (Association for Computing Machinery, New York, NY, USA, 2020).
 - [21] Y. Cui and S. Ramanathan, Substrate effects on metal–insulator transition characteristics of rf-sputtered epitaxial VO₂ thin films, *Journal of Vacuum Science & Technology A* **29**, 041502 (2011).
 - [22] Y. Zhou and S. Ramanathan, Heteroepitaxial VO₂ thin films on GaN: Structure and metal–insulator transition characteristics, *Journal of Applied Physics* **112**, 074114 (2012), <https://pubs.aip.org/aip/jap/article-pdf/doi/10.1063/1.4758185/15098031/074114.1.online.pdf>.
 - [23] G. Rampelberg, B. De Schutter, W. Devulder, K. Martens, I. Radu, and C. Detavernier, In situ X-ray diffraction study of the controlled oxidation and reduction in the V–O system for the synthesis of VO₂ and V₂O₃ thin films, *J. Mater. Chem. C* **3**, 11357 (2015).
 - [24] X. Ding, Y. Li, and Y. Zhang, Sol-Gel Derived Tungsten Doped VO₂ Thin Films on Si Substrate with Tunable Phase Transition Properties, *Molecules* **28**, 10.3390/molecules28093778 (2023).
 - [25] L. Feldman and J. Mayer, *Fundamentals of Surface and Thin Film Analysis* (P T R Prentice Hall, 1986).
 - [26] Z. Yang, S. Hart, C. Ko, A. Yacoby, and S. Ramanathan, Studies on electric triggering of the metal–insulator transition in VO₂ thin films between 77 K and 300 K, *Journal of Applied Physics* **110**, 033725 (2011), <https://pubs.aip.org/aip/jap/article-pdf/doi/10.1063/1.3619806/14060782/033725.1.online.pdf>.
 - [27] F. J. Wong, Y. Zhou, and S. Ramanathan, Epitaxial variants of VO₂ thin films on complex oxide single crystal substrates with 3m surface symmetry, *Journal of Crystal Growth* **364**, 74 (2013).
 - [28] Y. Muraoka and Z. Hiroi, Metal–insulator transition of VO₂ thin films grown on TiO₂ (001) and (110) substrates, *Applied Physics Letters* **80**, 583 (2002), <https://pubs.aip.org/aip/apl/article-pdf/80/4/583/10193268/583.1.online.pdf>.
 - [29] C. Chen, Y. Zhu, Y. Zhao, J. H. Lee, H. Wang, A. Bernussi, M. Holtz, and Z. Fan, VO₂ multidomain heteroepitaxial growth and terahertz transmission modulation, *Applied Physics*

- Letters **97**, 211905 (2010), https://pubs.aip.org/aip/apl/article-pdf/doi/10.1063/1.3519361/14441057/211905.1_online.pdf.
- [30] M. Liu, H. Y. Hwang, H. Tao, A. C. Strikwerda, K. Fan, G. R. Keiser, A. J. Sternbach, K. G. West, S. Kittiwatanakul, J. Lu, S. A. Wolf, F. G. Omenetto, X. Zhang, K. A. Nelson, and R. D. Averitt, Terahertz-field-induced insulator-to-metal transition in vanadium dioxide metamaterial, *Nature* **487**, 345 (2012).
 - [31] S. D. Ha, Y. Zhou, C. J. Fisher, S. Ramanathan, and J. P. Treadway, Abrupt Insertion Loss Drop by RF-Triggering of the Phase Transition in VO₂ CPW Switches, *IEEE Microwave and Wireless Components Letters* **24**, 575 (2014).
 - [32] J. Duchene, M. Terraillon, P. Pailly, and G. Adam, Filamentary Conduction in VO₂ Coplanar Thin-Film Devices, *Applied Physics Letters* **19**, 115 (1971).
 - [33] J. S. Lee, M. Ortolani, J. Kouba, A. Firsov, Y. J. Chang, T. W. Noh, and U. Schade, Electric-pulse-induced local conducting area and joule heating effect in VO₂/Al₂O₃ films, *Infrared Physics & Technology* **51**, 443 (2008).
 - [34] J. G. Simmons, Poole-Frenkel Effect and Schottky Effect in Metal-Insulator-Metal Systems, *Phys. Rev.* **155**, 657 (1967).
 - [35] X. Sun, Z. Qu, Y. Yuan, J. Yuan, E. Cheng, P. Wang, J. Hu, and Q. Wang, Role of Joule heating in the electro-induced metal-insular transition of a composite film filled with VO₂, *Materials Research Express* **8**, 035302 (2021).
 - [36] K. Fleck, C. La Torre, N. Aslam, S. Hoffmann-Eifert, U. Böttger, and S. Menzel, Uniting Gradual and Abrupt set Processes in Resistive Switching Oxides, *Phys. Rev. Appl.* **6**, 064015 (2016).
 - [37] H. Lu, M. Lei, C. Zhao, Y. Yao, J. Gou, D. Hui, and Y. Fu, Controlling Au electrode patterns for simultaneously monitoring electrical actuation and shape recovery in shape memory polymer, *Composites Part B: Engineering* **80**, 37 (2015).
 - [38] C. L. Gomez-Heredia, J. A. Ramirez-Rincon, J. Ordonez-Miranda, O. Ares, J. J. Alvarado-Gil, C. Champeaux, F. Dumas-Bouchiat, Y. Ezzahri, and K. Joulain, Thermal hysteresis measurement of the VO₂ emissivity and its application in thermal rectification, *Scientific Reports* **8**, 8479 (2018).
 - [39] M. Gurvitch, S. Luryi, A. Polyakov, and A. Shabalov, Treating the Case of Incurable Hysteresis in VO₂, *Future Trends in Microelectronics*, 395 (2010), Wiley Online Books.
 - [40] C. Koughia, O. Gunes, C. Zhang, S.-J. Wen, R. Wong, Q. Yang, and S. O. Kasap, Topology of conductive clusters in sputtered high-quality VO₂ thin films on the brink of percolation threshold during insulator-to-metal and metal-to-insulator transitions, *Journal of Vacuum Science & Technology A* **38**, 063401 (2020).
 - [41] C. Annasiwatta, J. Chen, J. M. Berg, A. Bernussi, Z. Fan, and B. Ren, Multi-physics modeling of hysteresis in vanadium dioxide thin films, in *2016 American Control Conference (ACC)* (2016) pp. 6905–6910.
 - [42] S. Wang, J. G. Ramirez, and I. K. Schuller, Avalanches in vanadium sesquioxide nanodevices, *Phys. Rev. B* **92**, 085150 (2015).
 - [43] G. M. Liao, S. Chen, L. L. Fan, Y. L. Chen, X. Q. Wang, H. Ren, Z. M. Zhang, and C. W. Zou, Dynamically tracking the joule heating effect on the voltage induced metal-insulator transition in VO₂ crystal film, *AIP Advances* **6**, 045014 (2016), https://pubs.aip.org/aip/adv/article-pdf/doi/10.1063/1.4948311/12876433/045014.1_online.pdf.