UV–vis–IR Broad Spectral Photodetectors Based on VO$_2$–ZnO Nanocrystal Films

Danting Xu,† Xia Zhu,† Jiakun An, Gaoyu Chen, Jianchun Bao, and Xiangxing Xu*

**ABSTRACT:** As a narrow band semiconductor at room temperature and a metallic material above ~68 °C, functional VO$_2$ films are widely investigated for smart windows, whereas their potential for ultraviolet–visible–infrared (UV–vis–IR) broad spectral photodetectors has not been efficiently studied. In this report, photodetectors based on VO$_2$–ZnO nanocrystal composite films were prepared by nanocrystal-mist (NC-mist) deposition. An enhanced photodetection switching ratio was achieved covering the ultraviolet to infrared wavelength. Due to the synergetic effect of nanosize, surface, phase transition, percolation threshold, and the band structure of the heterojunction, the transfer and transport of photogenerated carriers modulate the device performance. This study probes new chances of applying VO$_2$-semiconductor-based nanocomposites for broad spectral photodetectors.

1. INTRODUCTION

Photodetection has been applied to various applications, such as imaging,\textsuperscript{1} remote sensing,\textsuperscript{2} biological processes,\textsuperscript{3} optical communication,\textsuperscript{4} and target recognition.\textsuperscript{5} However, photoelectronic materials in traditional photodetectors work for certain spectral bands, such as zinc oxide (ZnO) for ultraviolet (UV),\textsuperscript{6} cadmium selenide (CdSe) for visible light,\textsuperscript{7} and silicon (Si) for visible to near-infrared detection.\textsuperscript{8} As a wide band gap semiconductor, ZnO is stable and has high carrier mobility, which can potentially improve the charge transport and enhance the device performance. In photovoltaic devices, ZnO films composed of ZnO nanocrystals (NCs) can serve as the electron transport layer.\textsuperscript{9–12} In photodetectors, hybridization of ZnO with a second semiconductor, e.g., perovskite, could achieve an ambipolar photoresponse, higher switching ratio, faster response speed, and higher response and detection rate than compared to corresponding monophase devices.\textsuperscript{13–16}

Vanadium dioxide (VO$_2$) is known as a functional material for smart windows,\textsuperscript{17–20} infrared stealth,\textsuperscript{21} imaging,\textsuperscript{22} data storage,\textsuperscript{23} memristors,\textsuperscript{24} tunable-frequency metamaterials,\textsuperscript{25} multifunctional sensors,\textsuperscript{26,27} etc. It undergoes a reversible metal–insulator transition at ~68 °C, which can be further lowered to room temperature by doping.\textsuperscript{28–30} Monoclinic VO$_2$ (M) is a low-temperature phase, which is a semiconductor and infrared-transparent, whereas high-temperature rutile VO$_2$ (R) is a metal phase with low near-infrared transition and low infrared radiation. VO$_2$ is also used for infrared photodetectors, e.g., the high photoresponse of heterostructural VO$_2$/V$_2$O$_5$ nanobeams for 990 nm light,\textsuperscript{31} VO$_2$ thin films prepared by the vapor transport method for 850 nm light,\textsuperscript{32} and heavily hydrogen-doped VO$_2$ nanoparticles for 780 nm light.\textsuperscript{33} The potential of VO$_2$ for a visible photodetector is also demonstrated, e.g., the use of tungsten-doped VO$_2$ single nanowires for photodetection under visible light excitation of 405, 532, and 660 nm.\textsuperscript{34} Recently, Wadsley B phase VO$_2$(B) was found to have broad-band photodetection performances from the visible to terahertz region (405 nm to 0.88 mm).\textsuperscript{35} However, studies on VO$_2$ for broad spectral photodetection covering the ultraviolet–visible–infrared (UV–Vis–IR) range are very limited.

In this report, a VO$_2$–ZnO composite nanomaterial system was investigated for broad spectral photodetectors. The VO$_2$–ZnO composite was prepared by the NC-mist deposition strategy. The ZnO ratio, temperature, vacuum, and light
wavelength-related performances were studied. An appropriate ZnO ratio would enhance the performance of the device compared with pure VO\textsubscript{2}. It was found that not only the contribution from the single phase—such as the ultraviolet photodetectivity of ZnO or the near infrared photodetectivity of VO\textsubscript{2}—works but also the NC surface and heterojunction band structure play important roles in the charge transfer and transport.

2. EXPERIMENTAL SECTION

2.1. Materials. NH\textsubscript{4}VO\textsubscript{3} (99%), N\textsubscript{2}H\textsubscript{4}·H\textsubscript{2}O (80%), HCl (98%), and HNO\textsubscript{3} (99.9%) were purchased from Aladdin Industrial Corporation. Zinc acetate dihydrate (99%), KOH (85%), n-butanol (99.5%), methanol (99.5%), and chloroform (99%) were bought from Sinopharm Chemical Reagent Co., Ltd. All of the chemicals were used without further purification.

2.2. Preparation of VO\textsubscript{2} NCs.\textsuperscript{36,37} Typically, NH\textsubscript{4}VO\textsubscript{3} (0.35 g) was added to deionized H\textsubscript{2}O (70 mL) and stirred for 10 min. HCl (1.5 mL, 1 M) was added dropwise slowly until the solution turned orange and transparent. Then N\textsubscript{2}H\textsubscript{4}·H\textsubscript{2}O (4.5 mL, 80%) was added, with the color changed from orange-yellow to dark green (in ∼5 min) and to wine red (in ∼8 min). After vigorous stirring for 4 h, the solution changed to turbid gray-green. The precipitate was collected by centrifugation. The collected precipitate was dispersed in H\textsubscript{2}O (45 mL) and sonicated for 15 min. Then diluted HNO\textsubscript{3} (5.25 mL, 0.1 M) was added dropwise. After stirring for 4 h, the solution was sealed in a 100 mL autoclave and reacted at 240 °C for 36 h. The product was collected, dried, and thermal treated at 750 °C in an Ar gas atmosphere for 2 h to get the VO\textsubscript{2} NCs.

2.3. Synthesis of ZnO NCs.\textsuperscript{38} Typically, zinc acetate dihydrate (3 g) was dissolved in methanol (150 mL) with stirring at 60 °C. A methanol solution of KOH (1.5 g, 65 mL) was added dropwise in 15 min. After 3 h of reaction with stirring, the solution was cooled down naturally. The ZnO NCs were collected by centrifugation (12 000 rpm) and washed twice with methanol. The ZnO NCs were dispersed in a solution of n-butanol–methanol–chloroform (volume ratio of 14:1:1) with a concentration of 6 mg/mL.

2.4. Device Fabrication and Measurements. The as-prepared VO\textsubscript{2} NCs were ground for 10 min in an agate mortar for further use. The ground VO\textsubscript{2} NCs (20 mg) were added to the ZnO NC solution in three ZnO proportions of 5, 10, and 20 wt %. The solution was diluted with H\textsubscript{2}O to 75 mL and sonicated 1 min for device fabrication. The indium tin oxide (ITO) glass (15 Ω/□) was cleaned with acetone, ethanol, and deionized water. The interdigital electrodes were patterned by laser etching and acid washing of the ITO glass with a gap.
width of 200 μm. On a heating stage of 150 °C, the VO₂−ZnO NCs were deposited onto the ITO interdigital electrodes by the NC-mist deposition of the VO₂−ZnO NC solution, forming a lateral structured ITO/VO₂−ZnO NCs/ITO device. The photodetection properties were measured by a Keithley 2636B source meter. A diode of 365 nm and lasers of wavelengths of 365, 525, and 1064 nm with power values of 1.51, 2.11, and 3.02 mW/cm², respectively, were used as the ultraviolet–near infrared light sources. A heater at 700 K was used as the excitation source working at ∼4100 nm. The device working bias voltage was 10 V if not specifically mentioned. The switching ratio (SR) is calculated by

\[ SR = \frac{|I_{\text{on}} - I_{\text{off}}|}{I_{\text{off}}} \]  

where \( I_{\text{on}} \) is the photocurrent and \( I_{\text{off}} \) is the dark current. The responsivity (R) defines the photocurrent generated per unit power of the incident light on the effective area of a photodetector and is calculated by

\[ R = \frac{|I_{\text{on}} - I_{\text{off}}|}{P_{\text{in}}A} \]  

where \( P_{\text{in}} \) is the light power and \( A \) is the effective area of the device. Detectivity (\( D^* \)) characterizes the detectable light level by the device and is given by

\[ D^* = \frac{R}{\sqrt{(2eR/\lambda)}} \]  

where \( e \) is the electronic charge and \( R \) is the responsivity of the device. Here, shot noise is used to calculate the detectivity, as the calculated value of Johnson noise is smaller, e.g., the values of shot noise and Johnson noise are \( 2.1 \times 10^{-15} \) and \( 4.8 \times 10^{-16} \) A for VO₂−20%ZnO, respectively.

### 2.5. Characterizations.

The crystal structures of VO₂ and ZnO NCs were characterized by powder X-ray diffraction (XRD) with graphite-monochromatized Cu Kα radiation (\( \lambda = 0.15406 \) nm). The morphologies were characterized by transmission electron microscopy (TEM) using a JEM-200CX with an accelerating voltage of 80 kV and scanning electron microscopy (SEM) using JEOL JSM-7600F equipped with an energy-dispersive spectroscopy (EDS) system. The UV–Vis–IR spectra were measured by a Varian Cary 50 spectrophotometer. The energy band structures of the ZnO and VO₂ NCs were measured by ultraviolet photoelectron spectroscopy (UPS) using an EscaLab 250Xi. Differential scanning calorimetry (DSC) trace was recorded on a Diamond DSC instrument.

### 3. RESULTS AND DISCUSSION

The schematic illustration of the photodetector preparation is shown in Figure 1a. Because the VO₂ NCs used here are thermally treated at elevated temperature, the crystal surface is

Figure 2. Photoresponse of VO₂, ZnO, and VO₂–ZnO devices under vacuum and 30 °C with excitation at (a) 365 nm, (b) 525 nm, (c) 1064 nm, and (d) ∼4100 nm.
clean without ligands. Their dispersion in solution is not as stable as ZnO NCs. Therefore, the common film preparation methods of spin-coating, dip-coating, and blade-coating are not applicable. Although introducing surfactants or soluble polymers as dispersing agents would help, their removal in the following steps would lead to the destruction of VO$_2$ or the film structure. To date, mist-assisted chemical deposition of functional thin films has been developed for ZnO, In$_2$O$_3$, and SnO$_2$ films used in solar cells, sensors, transistors, etc. 40−43 For the mist chemical deposition system, it is a challenge to prepare VO$_2$ films with phase purity. 44 To overcome this challenge, NC-containing mist-deposition is a newly developed technique and has been applied to prepare the GZO film. 45 Here, we use this method to prepare the VO$_2$−ZnO film. First, the VO$_2$−ZnO NC dispersion was atomized using an ultrasonic atomizer. The VO$_2$−ZnO NC-mist was carried by the N$_2$ flow to the substrate/electrodes on a heating stage. With an appropriate heating temperature (150 °C), the solvent of the mist evaporates quickly while depositing. At the same time, it will not lead to the degradation of the NCs. TEM characterization shows that the as-synthesized ZnO NCs are 3–5 nm and the VO$_2$ NCs are ∼50 nm on average (Figure 1b,c). XRD patterns (Figure 1d) indicate that the ZnO NCs are wurtzite structured (Joint Committee on Powder Diffraction Standards, JCPDS 89-7102) and VO$_2$ NCs are monoclinic structured (JCPDS 43-1051). The XRD pattern of the VO$_2$−20%ZnO film (Figure S1) shows the existence of VO$_2$ and ZnO feature peaks, suggesting their stability during the preparation. SEM images of the VO$_2$ and VO$_2$−ZnO NC films are shown in Figure 1e−g. Although these films are smooth macroscopically, they exhibit a porous feature on the nanometer scale. Due to the smaller size of ZnO NCs, the

Figure 3. (a) UPS spectra of VO$_2$ and ZnO NCs. (b) Band structure of the VO$_2$−ZnO type-II heterojunction. (c) DSC curves (up) and temperature-dependent transmittance spectra of the VO$_2$ nanocrystals (below). Temperature-dependent photodetection performances of the VO$_2$−20%ZnO device with excitation at (d) 365 nm, (e) 525 nm, and (f) 1064 nm under vacuum and with excitation at (g) 365 nm, (h) 525 nm, and (i) 1064 nm in air.
pores between VO₂ NCs are gradually filled by the increased content of the ZnO NCs. The thickness of the film can be controlled by the deposition time. A typical lateral image of VO₂–20%ZnO film is shown in Figure 1h, exhibiting good uniformity of thickness ∼1.1 μm.

Figure 2 shows the photodetection performance of the devices based on films of VO₂ NCs containing 0, 5, 10, and 20% ZnO NCs. At all of these excitation wavelengths ranging from ultraviolet to the infrared, the device made using pure VO₂ NCs shows the highest dark current, suggesting the good conductivity. Under ultraviolet excitation, the VO₂–5%ZnO and VO₂–10%ZnO devices show 10⁻⁸–10⁻⁹ lower dark current than the pure VO₂, ZnO, and VO₂–20%ZnO devices. This observation is consistent with the fact that the dark current of the ZnO film is illumination-history-dependent under ultraviolet excitation (Figure S2). It takes a long time of up to several hours for the dark current to drop down to the original dark current value range after illumination. A similar phenomenon was also reported in ZnO-based photodetectors.⁴⁶,⁴⁷ It could be caused by the illumination-induced trapped charges in ZnO NCs.⁴⁸ Thus, the prolonged recombination time enhances the dark current value in a period after ultraviolet excitation. Therefore, the low dark current of the VO₂–5%ZnO and VO₂–10%ZnO could be mainly due to the disconnected nature of both VO₂ and ZnO. This is consistent with the fact that the VO₂–20%ZnO device has a comparable response to ZnO at 365 nm excitation because of the percolation effect. UPS spectra were measured to determine the band structures of the ZnO and VO₂ NCs (Figure 3a,b). It shows that VO₂–ZnO forms a type-II semiconductor heterojunction. The conduction band of VO₂ is higher than that of ZnO. Therefore, at low ZnO content, when excited by ultraviolet, the transport of photogenerated electrons in ZnO together with those transferred from the VO₂ would be confined in discrete ZnO, resulting in a low current. When the ZnO ratio is increased to 20%, the responsivity and photodetectivity are increased to 0.462 mA/W and 2.72 × 10⁹ Jones, respectively, higher than 0.326 mA/W and 3.02 × 10⁹ Jones for the pure VO₂ NC device and 0.353 mA/W and 1.84 × 10⁹ Jones for the pure ZnO NC device. This suggests that 20% of ZnO exceeds the percolation threshold of the VO₂–ZnO nano composite, forming long-range connectivity of the ZnO NCs.

The performance of the device under visible light excitation at 525 nm, near-infrared at 1064 nm, and infrared at ∼4100 nm shares a similar behavior. The increased dark and light currents of VO₂–20%ZnO compared with those of VO₂–10% ZnO under visible-to-infrared excitation suggests the effective charge separation and positive contribution of ZnO to the current. The lower current of the nanocomposite than that of VO₂ is due to the segmentation effect of ZnO. Since ZnO has no absorption in these wavelengths, the photogenerated electrons are contributed by the VO₂ and transferred to ZnO. Although the responsivity and photodetectivity of the VO₂–ZnO devices for visible to near-infrared excitation are lower than the values of the pure VO₂ NC device, e.g., 10.1 mA/W and 4.19 × 10⁹ Jones for the pure VO₂ NC device, which decreased to 3.29 × 10⁻⁹ mA/W and 5.21 × 10⁹ Jones for the VO₂–20%ZnO device with excitation at 1064 nm, respectively. ZnO shows a positive contribution to the switching ratio. The switching ratio of the VO₂–20%ZnO device at 1064 nm is 8.95, higher than 2.68 of the pure VO₂ NC device. The enhancement of the switching ratio is also true for the ultraviolet and infrared excitations. It reaches 8.7 for the VO₂–20%ZnO device, higher than 1.14 for the pure VO₂ device and 4.46 for the pure ZnO device with 365 nm excitation. It is 2.12 for the VO₂–10%ZnO device, higher than 1.21 for the pure VO₂ device with ∼4100 nm excitation.

As VO₂ has a phase transition at 68 °C from the low-temperature M phase to the high-temperature R metallic phase (Figure 3c), it would be interesting to study the temperature-dependent photodetection. The temperature-dependent dark current of the VO₂–20%ZnO device was measured (Figure S3). It shows that the current remains almost unchanged before the M–R phase transition of VO₂, whereas it increases sharply around the phase transition point. As the excitation light power is too low to heat up the device reaching the phase transition point, the light-induced thermal effect has a negligible contribution to the responsivity of the device. Three temperatures of 30, 60, and 90 °C are selected to carry out the photodetection measurement of the VO₂–20%ZnO device (Figure 3d–f). It is found that with the temperature increasing to 90 °C, the photodetectivity and switching ratio for ultraviolet excitation increased to 2.74 × 10⁹ and 5.91, respectively; photodetectivity increased from 6.91 × 10⁶ Jones to 1.54 × 10⁷ Jones and the switching ratio of 1.15 was almost unchanged for 525 nm excitation; and photodetectivity increased to 7.37 × 10⁷ Jones and the switching ratio decreased to 1.28 for 1064 nm excitation. The excitation wavelength-dependent performance change with temperature is not surprising due to the phase change of VO₂ and different absorption ranges of ZnO and VO₂ NCs. It is noticed that the current increases with the temperature under the visible to near-infrared excitation, consistent with the VO₂ semiconductor to metallic phase transformation, suggesting that the charge carrier transport is possibly dominated by the hopping mechanism.⁴⁹–⁵¹ As shown in Figure 1, the VO₂–ZnO NC film prepared by the NC-mist deposition has a porous structure. The large specific surface is favorable to the adsorption of molecules in air such as H₂O, O₂, and CO₂, which would affect the photodetection. It shows that the current of the VO₂–20%ZnO device is lower in air than in vacuum (Figure 3g–i). However, the photodetectivity and switching ratio change trends are similar to those in vacuum except for the 365 nm excitation, which indicates that the adsorption states, especially the O₂ adsorption on ZnO surface defects, are sensitive to the ultraviolet light.⁵²–⁵⁴ In a control experiment, a nonporous spin-coated film made using the same ZnO NCs shows much higher conductivity and an enhanced detectivity of 2.30 × 10¹¹ Jones for 365 nm excitation (Figure S4). This suggests that the film structure significantly affects the device performance.

4. CONCLUSIONS

In summary, the potential of using VO₂–ZnO NCs for broad spectral photodetection was preliminarily investigated. Compared with the pure VO₂ device of the same structure, an enhanced switching ratio was achieved across the ultraviolet, visible, and infrared range. The nanosize of VO₂ and ZnO showed a prominent effect on the surface adsorption states and charge transport mechanism. The photodetectors exhibited temperature- and vacuum/air-dependent photoresponses. The band structure of the VO₂–ZnO system facilitates the electron transfer to the ZnO. Thus, the ZnO ratio regarding the percolation threshold in the composite is of critical importance to the device performance. Although the photodetectivity and
responsivity are not satisfactory for commercial applications at the present state, this study probes the possibility of utilizing VO$_2$-semiconductor-based nanocomposites for broad spectral photodetectors. Improvement could be expected by optimization of the material system, fabrication technique, and device structure.

**ACKNOWLEDGMENTS**

This work was financially supported by the National Natural Science Foundation of China (Nos. 21871143, 22175095, and 22075147).

**REFERENCES**

(1) Li, L.; Ye, S.; Qi, J.; Zhou, F.; Song, J.; Shen, G. Recent advances in perovskite photodetectors for image sensing. *Small* 2021, 17, No. 2005606.

(2) Refaat, T. F.; Abedin, M. N.; Bhagwat, V.; Bhat, I. B.; Dutta, P. S.; Singh, U. N. InGaSb photodetectors using an InGaSb substrate for 2 pm applications. *Appl. Phys. Lett.* 2004, 85, 1874–1876.

(3) Rezaei-Mazinani, S.; Ivanov, A. I.; Proctor, C. M.; Gkoupidenis, P.; Bernard, C.; Malliaras, G. G.; Ismailova, E. Monitoring intrinsic optical signals in brain tissue with organic photodetectors. *Adv. Mater. Technol.* 2018, 3, No. 1700333.

(4) Pospischil, A.; Humer, M.; Furchi, M. M.; Bachmann, D.; Guider, R.; Fromherz, T.; Mueller, T. CMOS-compatible graphene photodetector covering all optical communication bands. *Nat. Photonics* 2013, 7, 892–896.

(5) Xiong, J.; Li, F.; Zhao, N.; Jiang, N. Tracking and recognition of multiple human targets moving in a wireless pyroelectric infrared sensor network. *Sensors* 2014, 14, 7209–7228.

(6) Ning, Y.; Zhang, Z.; Teng, F.; Fang, X. Novel transparent and self-powered UV photodetector based on crossed ZnO nanofiber array homojunction. *Small* 2018, 14, No. 1703754.

(7) An, Q.; Meng, X.; Xiong, K.; Qiu, Y.; Lin, W. One-step synthesis of CdSe nanotubes with novel hollow tubular structure as high-performance active material for photodetector. *J. Alloys Compd.* 2017, 726, 214–220.

(8) Park, H.; Crozier, K. B. Vertically stacked photodetector devices containing silicon nanowires with engineered absorption spectra. *ACS Photonics* 2015, 2, 544–549.

(9) Li, S.; Zhang, P.; Wang, Y.; Sarvari, H.; Liu, D.; Wu, J.; Yang, Y.; Wang, Z.; Chen, Z. D. Interface engineering of high efficiency perovskite solar cells based on ZnO nanorods using atomic layer deposition. *Nano Res.* 2017, 10, 1092–1103.

(10) Bouhjar, F.; Derbali, L.; Mari, B. High performance novel flexible perovskite solar cell based on a low-cost-processed ZnO:Co electron transport layer. *Nano Res.* 2020, 13, 2546–2555.

(11) Chandrasekhar, P. S.; Dubey, A.; Qiao, Q. High efficiency perovskite solar cells using nitrogen-doped graphene/ZnO nanorod composite as an electron transport layer. *Sol. Energy* 2020, 197, 78–83.

(12) Chen, R.; Cao, J.; Duan, Y.; Hui, Y.; Chuong, T. T.; Ou, D.; Han, F.; Cheng, F.; Huang, X.; Wu, B.; Zheng, N. High-efficiency, hysteresis-less, uv-stable perovskite solar cells with cascade ZnO-ZnS electron transport layer. *J. Am. Chem. Soc.* 2019, 141, 541–547.

(13) An, J.; Chen, G.; Zhu, X.; Ly, X.; Bao, J.; Xu, X. Ambipolar photosresponse of CsPbX$_2$ZnO (X = Cl, Br, and I) heterojunctions. *ACS Appl. Electron. Mater.* 2022, 4, 1525–1532.

(14) Li, H.; Liu, B.; Lin, W.; Liu, Y.; Wang, Y.; Zhang, Z.; Xiong, L.; Tao, J. Enhancing performance of broadband photodetectors based on perovskite CsPbBr$_3$ nanocrystals/ZnO-microwires heterostructures. *Sci. Adv. Mater.* 2021, 13, 1748–1755.

(15) Pan, X.; Zhang, J.; Zhou, H.; Liu, R.; Wu, D.; Wang, R.; Shen, L.; Tao, L.; Zhang, J.; Wang, H. Single-layer ZnO hollow hemispheres enable high-performance self-powered perovskite photodetector for optical communication. *Nano-Micro Lett.* 2021, 13, No. 70.

(16) Shao, D.; Zhu, W.; Xin, G.; Liu, X.; Wang, T.; Shi, S.; Lian, J.; Sawyer, S. A high performance UV-visible dual-band photodetector based on an inorganic Cs$_x$Sn$_{1-x}$ perovskite/ZnO heterojunction structure. *J. Mater. Chem. C* 2020, 8, 1819–1825.

(17) Cui, Y.; Ke, Y.; Liu, C.; Chen, Z.; Wang, N.; Zhang, L.; Zhou, Y.; Wang, S.; Gao, Y.; Long, Y. Thermochromic VO$_2$ for energy-efficient smart windows. *Joule* 2018, 2, 1707–1746.
Tungsten and fluorine co-doping of VO
Vanadium dioxide: the multistimuli responsive material and its metamaterial resonance using vanadium dioxide. Smith, D. R.; Basov, D. N.; Dynamic tuning of an infrared hybrid-F.; Chae, B. G.; Yun, S. J.; Kim, H. T.; Cho, S. Y.; Jokerst, N. M.; Yoo, I. K.; Kim, J. S.; Park, B. H. Two series oxide resistors applicable to wood film for smart windows.

Vanadium dioxide for thermochromic smart window applications. Tang, S. H.; Zhang, X.; Sow, C. H.; Mhaisalkar, S. G. Highly sensitive and multispectral responsive phototransistor using tungsten-doped VO
and multispectral responsive photodetector dominated by bolometric effect. Yu, X.; Liu, D.; Liu, L.; Shen, D. Speed enhancement of ultraviolet detection.

Physical vapour deposition of vanadium dioxide for thermochromic smart window applications. Gilmore, R. H.; Winslow, S. W.; Lee, E. M. Y.; Ashner, M. N.; Burkhardt, W.; Christmann, T.; Franke, S.; Kriegseis, W.; Liao, F.; Lu, C.; Yao, G.; Yan, Z.; Gao, M.; Pan, T.; Zhang, Y.; Guo, X.; Tan, Y.; Hu, Y.; Zafar, Z.; Liu, J.; Zou, J. Single crystalline nanoparticles.

Inverse temperature by mist chemical vapor deposition. Miller, M.; Keilmann, F.; Chae, B. G.; Yun, S. J.; Kim, H. T.; Cho, S. Y.; Jokerst, N. M.; Smith, D. R.; Basov, D. N. Dynamic tuning of an infrared hybrid-metal metamaterial resonance using vanadium dioxide.

Phase-transition driven memristive system. Liao, F.; Lu, C.; Yao, G.; Yan, Z.; Gao, M.; Pan, T.; Zhang, Y.; Feng, X.; Lin, Y. Ultrastable flexible temperature-mechanical dual-parameter sensor based on vanadium dioxide Films. IEEE Electron Device Lett. 2017, 38, 1128–1131.

Tungsten and fluorine co-doping of VO
thin films. Thin Solid Films 2002, 402, 226–231.

Nanoplatelet, G. M. Gdoping of thermochromic VO
films enhances the optical transmittance and decreases the metal-insulator transition temperature. Appl. Phys. Lett. 2009, 95, No. 043503.

The multistimuli responsive material and its applications. Small 2018, 14, No. 1802052.

Influence of different additives on the synthesis of VO
polymorphs. Ceram. Int. 2013, 39, 8363–8376.

Single-domain-VO
heterostructure in nanobeam. Adv. Funct. Mater. 2014, 24, 1821–1830.

High quality VO
thin films synthesized from VO
powder for sensitive near-infrared detection. Sci. Rep. 2021, 11, No. 21749.

Ultrafast infrared photoresponse from heavily hydrogen-doped VO single crystalline nanoparticles. Nano Lett. 2020, 20, 2733–2740.

Highly sensitive and multispectral responsive phototransistor using tungsten-doped VO
nanowires. Nanoscale 2014, 6, 7617–7627.

Direct hydrothermal synthesis of monoclinic VO
(M) single-domain nanorods on large scale displaying magnetocaloric effect. J. Mater. Chem. 2011, 21, 4509–4517.