Single-Crystalline W-Doped VO₂ Nanobeams with Highly Reversible Electrical and Plasmonic Responses Near Room Temperature

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Single-crystalline vanadium dioxide (VO₂) nanostructures are of great interest because of their single-domain metal-to-insulator transition. In this paper, single-crystalline W-doped VO₂ nanobeams are synthesized for optical and electrical applications. As a result of differences in the polarization of the beams along their transverse and longitudinal axes, dual-surface plasmon resonance peaks at 1344 and 619 nm are generated, resulting in an increase in the solar modulating abilities of the VO₂ nanobeams. The conductivity of the single-crystalline W-doped VO₂ nanobeams changes by three to four orders of magnitude at the transition temperature, which is of great importance for electrical applications.

1. Introduction

Vanadium dioxide (VO₂) is a smart material that is characterized by a reversible phase transition from an insulating monoclinic phase (VO₂ (M), P 2₁/c) to a metallic rutile phase (VO₂ (R), P 4 ̅ mmn) at ~68 °C.[1–6] During the metal-to-insulator transition (MIT), a sudden drop in infrared transmittance above the transition temperature Ƭc makes it a promising candidate for use in thermochromic smart windows.[7–11] Recently, there has been some newly reported VO₂ nanostructures (W-doped VO₂@SiO₂ nanoparticles,[11b] VO₂ nanonets,[11c] TiO₂(R)/VO₂(M)/TiO₂(A) multilayer film[11d]) in smart window applications. An efficient way to reduce Ƭc without compromising the solar modulation ability of oxides in hot water under a high autogenous vapor pressure.[12] Tungsten (W⁶⁺) cations have been found to be the most efficient dopants for lowering Ƭc at a rate of ~20–28 K per at%.[22]

In the past, high temperature evaporation,[23–26] sol–gel methods,[27] and magnetron sputtering[28] have been used to fabricate nanostructured VO₂ materials using complex equipment. In contrast, hydrothermal synthesis is an alternative facile method to prepare nanostructured metal oxides at relatively low temperatures (<300 °C), owing to the increased solubility of oxides in hot water under a high autogenous vapor pressure.[29] Nanostructured VO₂ materials, including nanopowders[30,31] and nanoasterisks,[33] have been synthesized under hydrothermal conditions below 300 °C with polycrystalline characteristics, complicating studies of the single-domain metal–insulator phase transition. Hydrothermally synthesized nanorods[32] have previously been reported to be micron-sized or larger in length, limiting their use in smart applications. To the best of our knowledge, there is still no report of the hydrothermal synthesis and investigation of uniform single-crystalline W-doped VO₂ nanobeams that are below 100 nm in width and 500 nm in length, although high temperature evaporation has been used to fabricate similar structures.[34]

In this paper, we report a simple hydrothermal process to synthesize W-doped single-crystalline VO₂ nanobeams and propose a rolling mechanism to explain their structural evolution from the starting 2D V₂O₅·H₂O layered material to vanadium oxide nanowires/nanobeams and nanopowders. A uniform distribution of W dopants in the VO₂ nanobeams results in a high doping efficiency and a unique surface plasmon resonance (SPR). The SPR is favored in thermochromic smart window applications to enhance their solar modulation ability ΔƬsol (defined as the solar transmission difference above and below Ƭc). It occurs only in the metallic state of VO₂, leading to enhanced absorption at high temperature and consequently reducing transmission above Ƭc without compromising the transmission in the insulating state below Ƭc.

2. Results and Discussion

N₂H₄·H₂O is an effective reagent to synthesize VO₂ by reducing the V₂O₅ starting material (2V₂O₅+N₂H₄·H₂O→4VO₂+N₂+3H₂O)[35] However, residual H₂O₂ in the...
precursor can also react with the $\text{N}_2\text{H}_4\cdot\text{H}_2\text{O}$ ($2\text{H}_2\text{O}_2+\text{N}_2\text{H}_4\cdot\text{H}_2\text{O}\rightarrow\text{N}_2\text{H}_4\cdot5\text{H}_2\text{O}$). Therefore, the amount of $\text{N}_2\text{H}_4\cdot\text{H}_2\text{O}$ is critical for the synthesis of the VO$_2$ phase. Figure 1a shows X-ray diffraction (XRD) patterns of W-doped VO$_2$ hydrothermal products, showing phase evolution with increasing amounts of $\text{N}_2\text{H}_4\cdot\text{H}_2\text{O}$. When the addition of $\text{N}_2\text{H}_4\cdot\text{H}_2\text{O}$ was below 30 μL, a mixture of V$_6$O$_{13}$ and VO$_2$(R) was formed, primarily owing to the consumption of $\text{N}_2\text{H}_4\cdot\text{H}_2\text{O}$ by the residual H$_2$O$_2$ in the precursor. After increasing the amount of $\text{N}_2\text{H}_4\cdot\text{H}_2\text{O}$ to 35 μL, a highly crystalline VO$_2$ (R) phase (JCPDS #79-1655) was synthesized successfully. Upon further increasing the amount of $\text{N}_2\text{H}_4\cdot\text{H}_2\text{O}$ to 50 and 100 μL, the products were gradually reduced to V$_6$O$_{11}$ and V$_2$O$_3$, respectively. Only the intermediate VO$_2$(A) phase, which crystallized in tetragonal form with space group P4$_2$/nmc (JCPDS #42-876), could be obtained under the same hydrothermal conditions without W doping, suggesting that W doping reduces the energy barrier for VO$_2$(R) phase formation. A similar phenomenon has been observed in the synthesis of Mo-doped VO$_2$(M) nanorods, where only the VO$_2$(B) phase (monoclinic C2/m, JCPDS #81-2392) could be obtained without the addition of molybdic acid.$^{[36]}$

The morphology of the vanadium oxide products is shown in Figure 1b–f. Along with the phase evolution (V$_6$O$_{13}$→VO$_2$→V$_6$O$_{11}$→V$_2$O$_3$), the morphology gradually changed from nanowire (V$_6$O$_{13}$) to nanobeam (VO$_2$) to nanoparticle, with a continuous reduction in aspect ratio. As shown in Figure 1b, the V$_6$O$_{13}$ nanowires are ≈50 nm in width, with a length in the micron-size range and an aspect ratio of >50. With increasing reducing agent, the V$_6$O$_{13}$ nanowires reduce in length (Figure 1c). VO$_2$(R) nanobeams with a low aspect ratio (≈4–8) could be obtained by further increasing the amount of the reducing agent, with the width and length of nanobeams (Figure 1d) falling into the ranges 90–100 nm and 400–800 nm, respectively. Finally, V$_6$O$_{11}$ and V$_2$O$_3$ nanoparticles with mean
grain sizes of ≈50 nm were obtained as observed in Figure 1e,f, respectively. It is of interest that the morphology of the VO\textsubscript{2} product could be tailored by the W doping level as shown in Figure S1 (see the Supporting Information), where the nano-beams could be changed to the mixture of nanobeam and nanoparticles.

A rolling mechanism is proposed to explain the structural transformation from the layered starting material to the final low-dimensional nanostructures.\cite{37} As illustrated in Figure 2a and Figure S6 (see Supporting Information), the V\textsubscript{2}O\textsubscript{5}-H\textsubscript{2}O\textsubscript{2} precursor has a 2D sheet structure and a chemical composition of V\textsubscript{2}O\textsubscript{5}-1.6H\textsubscript{2}O, as confirmed by XRD (JCPDS #40-1296) and selected area electron diffraction (SAED), consistent with previous experimental results.\cite{38} As the amount of reducing agent N\textsubscript{2}H\textsubscript{4}-H\textsubscript{2}O ([N\textsubscript{2}H\textsubscript{5}]\textsuperscript{+}·OH\textsuperscript{−}) is steadily increased, the product is gradually reduced, following the phase evolution V\textsubscript{6}O\textsubscript{13}→VO\textsubscript{2}→V\textsubscript{6}O\textsubscript{11}→V\textsubscript{2}O\textsubscript{3}. With increasing temperature and pressure during the hydrothermal process, the lamellar structure tends to curl into 1D V\textsubscript{6}O\textsubscript{13} tubular structures, some of which continue to grow into solid V\textsubscript{6}O\textsubscript{13} nanowires by lateral growth (Figure 2b). As VO\textsubscript{2}, V\textsubscript{6}O\textsubscript{11} and V\textsubscript{2}O\textsubscript{3} do not have enough solubility to grow via Oswald ripening mechanism that would allow mass transfer from smaller nanocrystals to larger ones, the VO\textsubscript{2} nanobeams were formed with relative low aspect ratios (Figures 2c,1d), and the V\textsubscript{6}O\textsubscript{11}/V\textsubscript{2}O\textsubscript{3} nanpowders with the lowest solubility were obtained from the collapse of nanowires/ nanobeams. To summarize, starting from a layered V\textsubscript{2}O\textsubscript{5}-H\textsubscript{2}O\textsubscript{2} gel, nanostructured vanadium oxide can transform into 1D nanotubes/nanowires/nanobeams through rolling and finally collapsing into nanoparticles, through the phase evolution V\textsubscript{2}O\textsubscript{5}→V\textsubscript{6}O\textsubscript{13}→VO\textsubscript{2}→V\textsubscript{6}O\textsubscript{11}→V\textsubscript{2}O\textsubscript{3} (Figure 2c).

Figure 3a,b show high-resolution X-ray photoelectron spectroscopy (XPS) V 2p and W 4f scans of the W-doped VO\textsubscript{2} product, respectively. The binding energy for V 2p\textsubscript{3/2} was located at 516.3 eV, indicating a V\textsuperscript{4+} valence state and confirming the phase purity of the VO\textsubscript{2}. According to a calculation based on the V 2p and W 4f peaks, the W\textsuperscript{6+} doping level is measured to be 2.45 at%. Energy-dispersive X-ray secondary electron microscopy (EDX-SEM) analysis of the W-doped VO\textsubscript{2} nanobeams, shown in Figure 3d, indicates a doping level of ≈2 at% W, consistent with the value expected from the precursor solution and similar to the value of 2.45 at% obtained using XPS. Figure 3c shows a differential scanning calorimeter (DSC) curve recorded from the 2 at% W-doped VO\textsubscript{2} product upon heating and cooling in the temperature range 5 °C–60 °C under N\textsubscript{2} flow. The endothermic and exothermic
peaks upon heating and cooling indicate a latent heat of \( \Delta H = 15.14/18.97 \) J g\(^{-1}\), compared to the commercial product with \( \Delta H = 38.7/41.87 \) J g\(^{-1}\), resulting from a lattice distortion arising from the W\(^{6+}\) doping, since the energy barrier for the phase transition is closely related to the stability of the structure. As observed in the DSC curve, the phase transition temperature during heating and cooling is \( \tau_{c,h} = 23.1 \) °C and \( \tau_{c,c} = 14.9 \) °C, respectively, giving a \( \tau_{c} \) of 19 °C, consistent with the \( \tau_{c} \) reducing rate of W\(^{6+}\) (20–28 °C per at%) for a doping level of 2.45 at%. The W doping level can be controlled by the doping source H\(_2\)WO\(_4\), and the \( \tau_{c} \) for 1/1.5 at% W-doped VO\(_2\) is 42.5/34.4 °C (Figure S2, see Supporting Information).

Figure 4a shows an SAED pattern recorded from a single VO\(_2\) nanobeam. Two sets of diffraction spots are identified as the VO\(_2\)(R) and VO\(_2\)(M) phases and are indicated using black and red indices. A corresponding bright-field transmission electron microscope (BF-TEM) image in Figure 4b shows that the growth direction of the nanobeam is along the [001] direction. Corresponding dark-field (DF) TEM images along the (001) and (010) directions are shown in Figure 4c,d, respectively. Brighter layers with widths of a few nanometers, which are visible in Figure 4c, are attributed to slight misorientation of the (020) planes in the lateral direction. Interestingly, the DF-TEM image in the (010) direction has a smaller outer contour compared to the BF and DF (100) TEM images, suggesting that the (010) planes are not diffracting strongly, for a similar reason to the misorientation observed in the DF (100) TEM image. SAED patterns did not change when the electron beam was moved along each nanobeam, revealing their invariant crystalline nature. Figure 5 shows high-angle annular DF scanning TEM (HAADF STEM) and EDX STEM maps of VO\(_2\) nanobeams. Figure 5a shows a low-magnification HAADF STEM image of several VO\(_2\) nanobeams, in which whiter areas correspond to the superposition of more than one nanobeam. The image confirms that the nanobeams have widths of \( \approx 100 \) nm and lengths below \( \approx 800 \) nm, in accordance with the SEM results. A high resolution HAADF STEM image shown in Figure 5b gives an indication of the replacement of V by W atoms in the VO\(_2\) lattice, as marked by arrows, indicating efficient doping by W\(^{6+}\), where the W atoms with larger atomic number are brighter than the V atoms, arising from their different contributions to the elastic scattering signals collected by the detector. Moreover, as shown in the EDX STEM maps (Figure 5d,e), the W atoms are dispersed uniformly in the nanobeam.

2.1. Optical Properties

Temperature-dependent UV–Vis–NIR spectra were recorded in the temperature range 10 °C–40 °C and plotted in the form %T (transmission) vs. \( \lambda \), as shown in Figure 6a. As reported in the literature,\(^{[19]}\) plasmonic metal nanobeams can exhibit two SPR peaks due to polarization along their transverse and longitudinal axes. When the VO\(_2\) nanobeams were heated from 20 to 40 °C, a pair of extinction peaks at 619 and 1344 nm was observed and attributed to transverse (\( \lambda_{SPR,T} = 619 \) nm) and longitudinal (\( \lambda_{SPR,L} = 1344 \) nm) SPR bands of metallic VO\(_2\) above 20 °C, which is quite different from the single SPR peak around 600 nm for VO\(_2\) nanoparticle patterns.\(^{[40]}\) As the short-wavelength incidence in the NIR region carries more energy, the expanded %T
contrast in this region arising from the SPR should contribute largely to the enlargement of $\Delta T_{sol}$, which has also been proved in the VO$_2$@SiO$_2$ nanostructures.\[^{[41]}\] Owing to the wide length distribution of the nanobeams, the full width at half maximum (FWHM) of the longitudinal SPR band at 1344 nm is 567.9 nm, which is much wider than that of the transverse SPR band at 619 nm (FWHM = 278.3 nm) (Figure 6b). To the best of our knowledge, this is the first report of temperature-dependent dual SPR peaks in VO$_2$ nanostructures. This dual SPR peaks could offer the tunability of the transmission contrast at different wavelength, which could be explored for other applications.\[^{[12b–d]}\]

The largely depressed SPR intensity (4.0% to 2.8% and 2.7% to 1.3% for transverse and longitudinal SPR, respectively) from 40 °C to 20 °C suggests a progressive transition from the metallic phase to the semiconducting phase, with a $\tau_c$ of 19 °C. Upon further cooling, the SPR disappeared at 15 °C, indicating the completion of the MIT. By reducing the W doping level from 2 at% to 1.5/1.0 at%, the morphology was changed from nanobeams to the mixture of nanobeams and nanoparticles (Figure S1, Supporting Information), and the positions of the SPR peaks were blue shifted from 1344/619 nm to 1290/530 nm (Figure S3, see Supporting Information), mainly owing to the decrease of aspect ratio. As shown in Figure 6c, the IR transmittance contrast (%$T_{lum}$ = 10 °C–%$T_{sol}$ > 10 °C) at a wavelength of 2500 nm first increased rapidly upon heating below 20 °C and then reached a stable value above 30 °C, which also indicated an MIT transition at a relatively low temperature. The %$T$ hysteresis loop at 2500 nm was measured in the temperature range 10 °C to 40 °C. As shown in Figure 6d, transition on heating/cooling gradually proceeds in the range from 15 °C to 30 °C /30 to 10 °C, with maximal change happening around 22/15 °C. The best-fitting result to the heating and cooling %$T$ data gives $\tau_{ch} = 21.6$ °C, $\tau_{cc} = 14.4$ °C and $\tau_c = (\tau_{ch} + \tau_{cc}/2) = 18$ °C, similar to the DSC result. The MIT sharpness ($=2.0$) is comparable to the reported results. The MIT range of the W-doped VO$_2$ should be ascribed to the generated free electron carriers\[^{[4]}\] as well as the extra strains resulted from the atom replacement of V$^{4+}$ by W$^{6+}$.[^42]

Figure 7a shows the temperature-dependent $T_{lum}$ and $\Delta T_{sol}$ for the VO$_2$ nanobeams. On cooling from 40 °C to 13 °C, $T_{lum}$ shows a slight change from 26.3% to 27.8%, while $\Delta T_{sol}$ increases steadily from 2.1% to a peak value of 5.0% at 15 °C, before dropping to 4.0% at 13 °C. The sharp decrease in $\Delta T_{sol}$ above 15 °C is ascribed to the obvious %$T$ bump at around 800 nm, since a sharp increase in %$T$ in the metallic state can reduce the $\Delta T_{sol}$ value seriously. $\Delta T_{IR}$ also exhibits a peak value (6.8%) at 15 °C, as shown in Figure 7b, which can also be attributed to the %$T$ bump in the metallic state arising from the two SPR peaks from the VO$_2$ nanobeams. However, the thermochromic properties ($T_{lum} = 26.0\%, \Delta T_{sol} = 5.0\%$) of the thin film composed of beams cannot reach the highest value ($T_{lum} = 56.0\%, \Delta T_{sol} = 8.7\%$) as reported for the W-doped VO$_2$ nanoparticles.\[^{[11b]}\] It is of interest that after adding additional 30 μL NH$_3$·H$_2$O (30 wt%) into the precursor, the hydrothermal product could be transformed from VO$_2$ nanobeams to VO$_2$ nanoparticles (average grain size = 30 nm), and the latter exhibited better performance with $T_{lum} = 31.2\%, \Delta T_{sol} = 6.4\%$ (Figure S8, Supporting Information), which is still lower than the best result, mainly due to the larger grain size (30 vs. 18.9 nm).
the VO₂ nanobeams were dispersed in ethanol and coated to show the FET device geometry used in this study, in which nature of the as-fabricated nanobeams. The inset in Figure 8d shows the FET device fabricated with a channel of W-doped VO₂ nanobeams. Under a gate voltage of 2 V and below 11 °C, the drain current increases slowly with drain voltage (Figure 8b). When combined with the I vs. VGS curves (Figure 8c), this result indicates that the drain current increases sharply above 12 °C. Moreover, the temperature-dependent drain current for VD = 1 V and VGS = 2 V increases sharply for temperatures above 12 °C (Figure 8d), indicating the MIT at this temperature. The decrease of drain current with increasing the gate bias above 12 °C should be due to the gate-source leakage, arising from the transition from insulator to metal of the nanobeams. No leakage current through the dielectric SiO₂ layer can be found in the test. For these FET measurements, τC is measured to be ≈12 °C. Since the measurement was performed at the near ambient temperature, the extra strain from the thermal mismatch between the nanobeams and the substrate should be neglected. The reduction of τC from 19 °C to 12 °C should be mainly ascribed to the applied electric field. Therefore, the FET device fabricated with a channel of W-doped VO₂ nanobeams shows the advantages of a large magnitude resistance reduction, as well as a lower electrically measured value of τC.

3. Conclusion

In summary, nanostructured W-doped vanadium oxide materials have been synthesized using a hydrothermal approach from a layered V₂O₅-H₂O₂ gel. By tuning the addition of N₂H₄·H₂O, the evolution of phase and morphology from V₂O₃ (nanotubes/nanowires) to VO₂ (nanobeams) to V₆O₁₁ (nanopowders) during the hydrothermal process could be observed. A rolling mechanism is proposed to explain the synthesis of such nanotube/nanowire/nanobeam structures from 2D precursors, a confirmed by TEM images. W doping is found to be critical for the formation of the VO₂(R) phase, since only the intermediate VO₂(A) could be obtained under the same synthesis conditions without doping, suggesting a reduction in phase formation energy barrier with doping. Uniform single-crystalline VO₂ nanobeams showed a pair of SPR peaks in the metallic state arising from polarization along the transverse and longitudinal axes. The single-crystalline W-doped VO₂ nanobeams exhibit an increase in electrical conductivity across τC by three to four orders of magnitude, i.e., one to two orders of magnitude higher than usually reported. The low-temperature synthesis of uniform single-crystalline VO₂ nanobeams should facilitate their room temperature applications in a variety of areas of research, such as thermochromic windows, FET devices, and smart sensors.

4. Experimental Section

All of the chemicals V₂O₅ (99.6%, Alfa Aesar), H₃WO₄ (99.9%, Alfa Aesar), N₂H₄·H₂O (99.9%, Alfa Aesar), and H₂O₂ (30 wt%, Sigma-Aldrich) were used as received without any further purification.

Hydrothermal Synthesis of Vanadium Oxide Materials: V₂O₅ (182 mg) and H₃WO₄ (10 mg) powder were added to H₂O₂ (5 mL, 30 wt%) preheated at 90 °C with stirring. After vigorous evaporation, a dark brown W-doped V₂O₅-H₂O₂ precursor sol was obtained, followed by the addition of deionized (DI) water (15 mL). The sol was reduced by...
N$_2$H$_4$·H$_2$O (25/30/35/50/100 μL) and then quickly sealed in a 100 mL Teflon-lined autoclave. The hydrothermal reaction was performed at 260 °C for 24 h in an oven. After cooling in air, the products were collected and washed with copious amounts of DI water and acetone several times by centrifuging (10 000 rpm). Ultimately, the products were dried in vacuum at 50 °C for 12 h.

**Characterization:** The phase of the products was characterized with a Shimadzu XRD-6000 X-ray diffractometer (CuKα, λ = 0.15406 nm) using a voltage of 40 kV and a current of 30 mA at an X-ray grazing angle of 1.0°. Their morphology was determined using a field emission scanning electron microscope (FESEM, JSM-7600F, JEOL, Japan) at an accelerating voltage of 5 kV. For conventional transmission electron microscopy (TEM) studies, i.e., using selected area electron diffraction (SAED), bright field (BF) and dark field (DF) imaging, an FEI Tecnai G2 (FEI Company, Eindhoven, The Netherlands) microscope was used at an accelerating voltage of 200 kV. For high-resolution (HR) high angle annular dark field (HAADF) scanning (S-)TEM and energy-dispersive X-ray (EDX) studies, a probe-aberration-corrected FEI Titan microscope (FEI Company, Eindhoven, The Netherlands) was used at an accelerating voltage of 200 kV. This microscope is equipped with a four quadrant EDX detector and the aberration coefficients of the probe forming system are corrected to fourth order. The elemental chemical states of the samples were measured using X-ray photoelectron spectroscopy (XPS, Kratos Axis Ultra, UK). An Al Kα (1486.6 eV) monochromatic X-ray source was used with an emission current of 10 mA and an anode HT of 15 kV. C 1s (284.5 eV) was used for spectrum calibration. DSC data were collected using a differential scanning calorimeter (DSC Q10, TA Instruments, USA) in the temperature range 5 °C–60 °C under a N₂ atmosphere.

**Figure 6.** a) UV–Vis–NIR spectra recorded in the temperature range 10 °C to 40 °C. b) SPR peaks of the %T spectra at 20 °C (blue line), with Gauss fitting (black and red lines) and base line subtract. c) %T contrast (%T$_{2500}$=10 °C–%T$_{>2500}$) at 2500 nm. d) Temperature-dependent %T hysteresis loop recorded at a wavelength of 2500 nm. The solid line represents a best-fitting result.

**Figure 7.** a) Thermochromic properties and b) IR modulating ability for a thin film deposited on a glass substrate with 2 at% W-doped VO₂ nanobeams under temperatures from 13 to 40 °C. ΔT$_{sol/IR}$ was calculated from ΔT$_{sol/IR}(T) = T_{sol/IR}(10 °C) − T_{sol/IR}(T)$. 

Transmittance spectra in the range 250–2500 nm were measured using a UV–Vis–NIR spectrophotometer (Cary 5000, Agilent Ltd, USA) equipped with a Linkam PE120 system Peltier heating & cooling stage. The integrated visible transmittance ($T_{\text{lum}}$, 380–780 nm) and solar/IR transmittance ($T_{\text{sol}}$, 280–2500 nm; $T_{\text{IR}}$, 780–2500 nm) were calculated based on the recorded %T spectra using the expression
\[
\int \phi_{\text{lum}}(\lambda) \frac{d\lambda}{T(\lambda)} + \int \phi_{\text{sol/IR}}(\lambda) d\lambda
\]
where $T(\lambda)$ is the recorded film transmittance, $\phi_{\text{lum}}$ is the standard luminous efficiency function for the photopic vision of human eyes\[^{44}\] and $\phi_{\text{sol/IR}}$ is the solar/IR irradiance spectrum for air mass 1.5 (corresponding to the sun standing 37° above the horizon).\[^{45}\] The hysteresis loop of %T at a wavelength of 2500 nm was measured at temperatures ranging from 10°C to 40°C. In order to attain the phase transition temperature $\tau_0$, the temperature-dependent heating and cooling %T($\tau$) data were fitted using a sigmoidal function of the form:
\[
\%T(\tau) = A_2 + (A_1 - A_2) / \left[ 1 + \exp(\tau - \tau_c) / B \right]
\]
where $\tau$ is the temperature in °C and $A_1$, $A_2$, $\tau_c$, and $B$ are fitting parameters. Two phase transition temperatures $\tau_{c,h}$ and $\tau_{c,c}$ were obtained in the heating and cooling cycles, respectively, and the average phase transition temperature was defined as $\tau_0 = (\tau_{c,h} + \tau_{c,c}) / 2$. $\Delta \tau_c = \tau_{c,h} - \tau_{c,c}$\[^{46}\] The integrated transmittance variation $\Delta T_{\text{lum/sol/IR}}$ compared to the transmission at 10°C is given by the expression $\Delta T_{\text{lum/sol/IR}} = T_{\text{lum/sol/IR}}(10^\circ \text{C}) - T_{\text{lum/sol/IR}}(\tau)$.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

Figure 8. a) Hysteresis loop of the temperature-dependent resistance of W-doped VO$_2$ nanobeams. b) Temperature-dependent I/V curve measured at a gate voltage of 2 V. c) Temperature-dependent I/V$_G$ curve measured at a drain voltage of 1 V. d) Temperature-dependent drain current measured at a gate voltage of 2 V and a drain voltage of 1 V.

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