

Non-negligible photostriction that accompanies the photoinduced phase transition process in VO₂

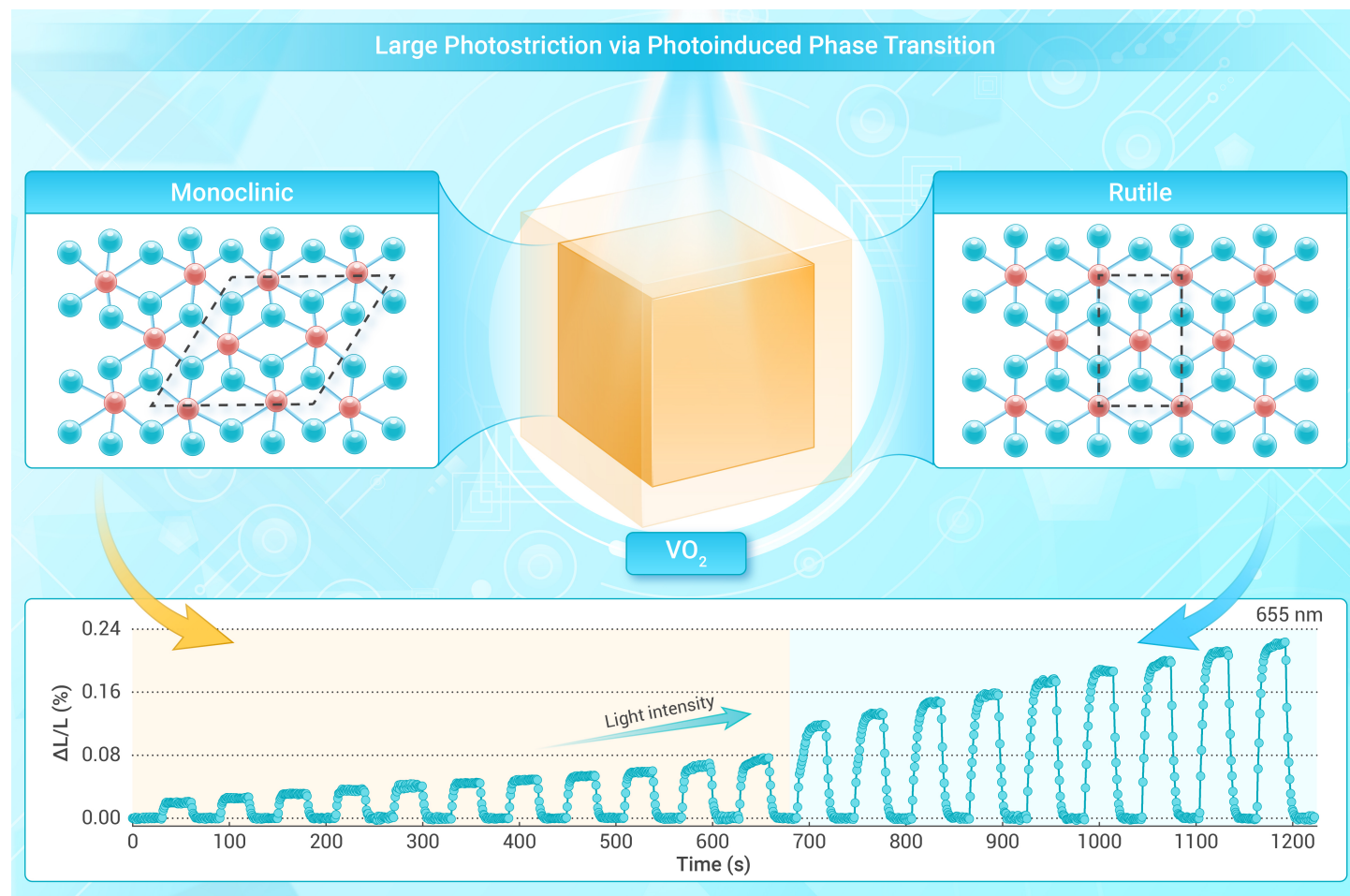
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GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- A new approach is introduced to improve the photostriction of inorganic materials.
- A large photoinduced strain comparable to the piezoelectric strain is induced in VO₂ ceramics.
- The light-wavelength-selective photostriction behavior in VO₂ is elucidated.

Non-negligible photostriction that accompanies the photoinduced phase transition process in VO₂

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VO₂ experiences a transition from an insulating monoclinic phase to a metallic rutile phase near room temperature, which can be triggered by photoexcitation. This unique phenomenon highlights the significant potential of VO₂ in optoelectronic applications. However, the photoinduced shape deformation, also known as photostriction, which occurs during this phase transition has been largely overlooked. Here, we present findings on the photostriction of VO₂ ceramics and investigate the impact of photoinduced phase transition on its photostriction behavior. Large photostriction exceeding 0.1% is achievable in VO₂ ceramics when illuminated by both 405 and 655 nm monochromatic laser. In contrast to the majority of inorganic photostrictive materials, VO₂ demonstrates a nonlinear increase in photostriction as light intensity increases. Upon surpassing the threshold light intensity, the photo-triggered M-to-R phase transition leads to an anomalous increase, approximately 40%, in photostriction. Furthermore, the photoexcited structural evolution and the variation in photostrictive response to different light wavelengths are also depicted by *ab initio* molecular dynamics simulations. This study not only demonstrates VO₂ as an excellent inorganic material for photo-actuating applications, but also validates the effectiveness of utilizing photoinduced phase transition to explore high-performance inorganic photostrictive materials.

INTRODUCTION

VO₂ is a prototypical strongly correlated materials, exhibiting intriguing insulator-metal transition (IMT).¹⁻⁴ It undergoes a first-order phase transition from monoclinic structure (insulator) to rutile structure (metal) thermally at around 68°C, resulting in attractive changes in electrical resistance and optical properties due to the strong interactions of multi-degree of freedom such as charge, lattice, orbit and spin.^{3,5-10} Most notably, this phase transition can also be triggered by light, promising great potentials in optical switchable smart devices for optical modulators, polarimetric imaging, optical communication, and beyond.¹¹⁻¹⁴ Additionally, it is noteworthy that the IMT of VO₂ exhibits a first-order nature, leading to a discontinuous volumetric change in the unit cell.¹⁵ As the lowering of symmetry in R-to-M phase transition (Figure 1A), the unit cell doubles with a volume change by approximately 0.045%.¹⁶ Such a distinct volume change during the photoexcited phase transition is expected to induce substantial strains, potentially impacting the design, performance, stability and longevity of optoelectronic devices based on the IMT of VO₂.

The equilibrium VO₂ at room temperature exhibits a monoclinic structure, characterized by V-V pairs dimerized along the *a* axis (Figure 1A).^{1,11} After reaching a specific level of photoexcitation intensity, the structure undergoes a transformation into a non-equilibrium tetragonal rutile phase, accompanied by the melting of V dimers. Based on *ab initio* molecular dynamics (AIMD) simulations, as increasing the photoexcitation, the V-V dimers dilate and tilt to align along the *a* axis of the monoclinic cell, leading to the elongation of the lattice parameter *a* and the expansion of the lattice volume while minor changes are observed in the lattice parameters *b* and *c* (Figures 1B & S1). Meanwhile, the volume change exhibits a linear increase below 1.76% photoexcitation, but an abrupt change occurs between 1.76% and 2.25% excitations, indicating the M-to-R phase transition accompanied by the

unlock of V-V dimers. The phenomenon of photoinduced volume changes in materials is also known as photostrictive effect, demonstrating the capability to directly convert optical energy into mechanical strain.¹⁷⁻¹⁹ However, the photostrictive performance of VO₂, to the best of our knowledge, has been largely overlooked for a significant period of time.

In this work, high-quality VO₂ ceramics were fabricated by fast spark plasma sintering (SPS) technique under vacuum environment to avoid the oxidation of V⁴⁺, then the photostriction was characterized by using high precision capacitance dilatometer. We observe a significant photostrictive response of VO₂ to 655 nm monochromatic laser light, with an abnormal enhancement occurring at a specific light intensity, which is attributed to volumetric expansion accompanying the photoinduced M-to-R phase transition. Under 405 nm laser illumination, the photostrictive response is markedly reduced compared to that observed under 655 nm laser light, as elucidated by our simulations. The longer wavelength of 655 nm results in the predominant excitation of electrons from the V-V bonding states, thereby facilitating the direct dissociation of the V-V dimer. Conversely, with the shorter wavelength of 405 nm, the most excited electrons originate from deeper levels rather than the V-V bonding states, rendering them ineffective in achieving the M-to-R phase transition and photostrictive response. Our findings demonstrate VO₂ as an excellent inorganic material for photo-actuating applications, also provides photoinduced phase transition as a promising strategy for exploring high-performance inorganic photostrictive materials.

MATERIALS AND METHODS

Fabrication of VO₂ ceramics

High-purity raw VO₂ (99%) powders were purchased from Aladdin. Before sintering, the VO₂ powders were ball milled with ethanol at 400 rpm for 10 h, then dried in oven and sieved with 200 mesh screen to obtain uniform fine powders. The treated VO₂ powders were sintered by fast spark plasma sintering (SPS-211Lx, Fuji Electronic Industrial CO., LTD, Japan) in a vacuum environment to avoid the oxidation of V⁴⁺. The powders were put into a graphite die in 10 mm diameter and sintered at 750°C under 40 MPa uniaxial pressure for 5 mins, and the heating speed was 100 °C/min. The as-sintered ceramics were annealed at 400°C for 2 hours to remove the residual carbon.

Characterization of structure, morphology, and photostriction

The phase structure of VO₂ ceramics was identified by a high-resolution X-ray diffractometer (Bruker D8 ADVANCE) with Cu *ka* radiation and refined by Rietveld method using GSAS suite.^{20,21} The variable temperature XRD patterns were collected by a high-resolution X-ray diffractometer (Bruker D8 Discover). The thermal phase transition temperature was measured by Differential Scanning Calorimetry (METTLER TOLEDO DSC 3+) under nitrogen atmosphere with a heating rate of 10 °C/min. Variable temperature Raman spectra were collected by a laser Raman spectrometer (Horiba LabRAM HR Evolution) with 532 nm laser source. The microstructure of the ceramics was observed by a scanning electron microscope (ZEISS Sigma 300, Germany). The UV-vis absorption spectrum was measured using the diffuse reflection method by a PerkinElmer Lambda 950 UV/VIS/NIR spectrometer. The photostriction performance was measured using a capacitance dilatometer. The VO₂ ceramic was machined into a 7 × 2 × 0.2 mm³ thin

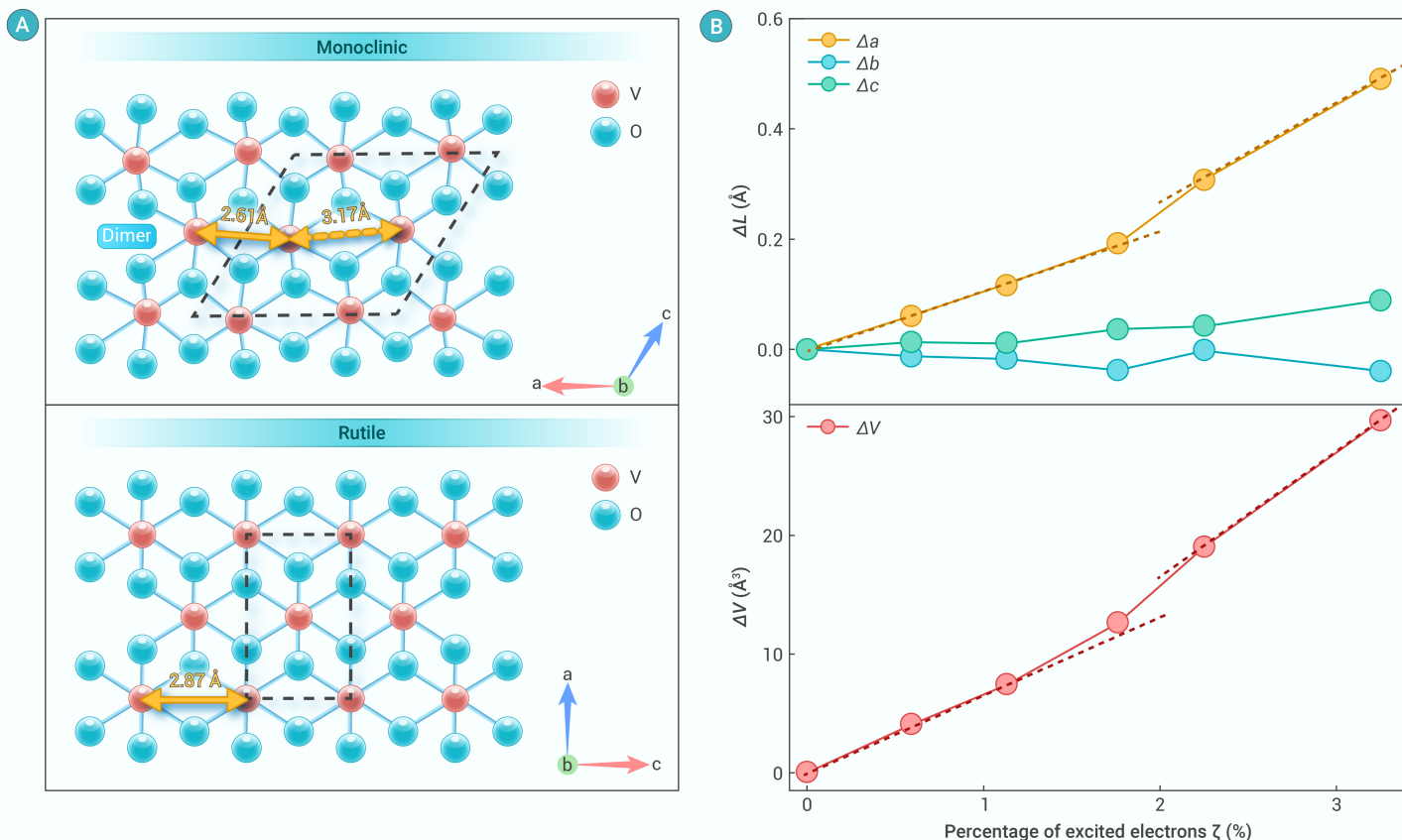


Figure 1. Crystallographic structure of VO₂ (A) in monoclinic phase (top) and rutile phase (bottom). The black dot boxes represent the unit cell of each structure. (B) Variations in lattice parameter *a*, *b*, *c* and volume changes ΔV as a function of the percentage of photoexcited electrons.

slice. Monochromatic lasers with wavelength of 405 and 655 nm were used as light source (LSR405NL-250 and LSR655NL-550, LASEVER, China). Both the 405 and 655 nm lasers show an elliptical spot, and their spot size are 3.2 mm (minor axis) x 4.0 mm (major axis) and 4 mm (minor axis) x 2.6 mm (major axis), respectively. The deformation along the length direction of the thin slice sample was collected by the capacitance dilatometer when the laser was illuminating along the thickness direction. The temperature changes of the illuminated area of the sample were monitored by a *k*-type thermocouple. The transient reflection spectra were collected at room temperature by using a femtosecond transient absorption spectrometer (FemtoFrame-INF, IBPhotonics LTD, Sofia, Bulgaria). The wavelength of pump is 347 nm, pump spot size is 0.18 mm in diameter, and pump pulse energy is 0.75 μJ.

Theoretical simulations

All calculations are performed utilizing the PWmat package,²² incorporating the local density approximation functional (LDA) + *U* exchange-correlation with Hubbard *U* = 3.4 eV.²³ Our simulation model comprises a 96-atom supercell, utilizing a plane-wave basis with a cutoff energy of 45 Ry. We adopted a 2×2×2 Monkhorst-Pack *k*-point mesh for Brillouin-zone sampling. To induce photoexcitation under varied laser fluences and wavelengths, a time-dependent external electric field was applied in a Gaussian shape within real-time Time-Dependent Density Functional Theory (TDDFT) simulations,²⁴

$$E(t) = E_0 \cos(\omega t) \exp[-(t - t_0)^2 / (2\sigma^2)], \quad (1)$$

where the photon energy $\omega = 1.89$ eV (655 nm), or 3.06 eV (405 nm), a time delay of $t_0 = 25$ fs, and a width parameter $\sqrt{2}\sigma = 10$ fs. The electric field E_0 is adjusted to achieve distinct electronic excitations (Supplemental information Figure S4 & S6). Based on the photoexcited carriers, *ab initio* molecular dynamics simulations in the NPT ensemble were performed using a time step of 1 fs. Subsequently, structural relaxation was conducted to reach a quasi-equilibrium state.

RESULTS AND DISCUSSION

Characterization of phase structure

Figure 2A presents the X-ray diffraction (XRD) refinement data of VO₂ ceramic sintered at 750°C by SPS. Monoclinic space group *P*₂₁/*c* was used for the Rietveld refinement. The calculated diffraction pattern matches well with the observed XRD data, indicating the monoclinic phase of VO₂ ceramic. The fitting quality is evaluated by the reduced $\chi^2 = 1.73$, $R_{wp} = 12.2\%$ and $R_p = 8.2\%$. The SPS-sintered VO₂ ceramic was annealed at 400°C for 2 hours in air before XRD measurement, therefore the VO₂ ceramic is thermally stable in air up to 400°C without obvious oxidation. The differential scanning calorimetry (DSC) curve given in Figure 2B exhibits a clear endothermic peak at around 67.6°C, indicating the typical VO₂ phase transition from room-temperature monoclinic structure to high-temperature rutile structure. Figure 2C shows the structural evolution of VO₂ ceramic as increasing the temperature from room temperature to 100°C. The XRD pattern of rutile structure is quite similar with the monoclinic structure, but the enlarged (0 1 1) peak of monoclinic phase and (1 1 0) peak of rutile phase clearly indicate the phase transition temperature between 65 to 70°C. The variable temperature Raman spectra also evidence the phase transition temperature at the same temperature range (Figure 2D), which is consistent with the DSC result. Figure 2E gives the cross-section scanning electron microscope (SEM) image of the SPS-sintered VO₂ ceramic, showing compact microstructure with sharp polyhedral grains. The smooth UV-vis spectrum in Figure 2F implies the good optical absorption ability of VO₂ ceramic over the visible light range.

Photostrictive performance of VO₂ ceramic

The photostrictive performance of VO₂ ceramic was measured by using capacitance dilatometer method.²⁵ Considering the strong visible-light response of VO₂ ceramic (Figure 2F), 405 and 655 nm monochromatic lasers were, respectively, applied as light source for the photostriction measurement. Figures 3A-B give the laser-intensity dependent photostriction of VO₂ ceramic for 405 and 655 nm lasers, respectively. For both lasers, the defor-

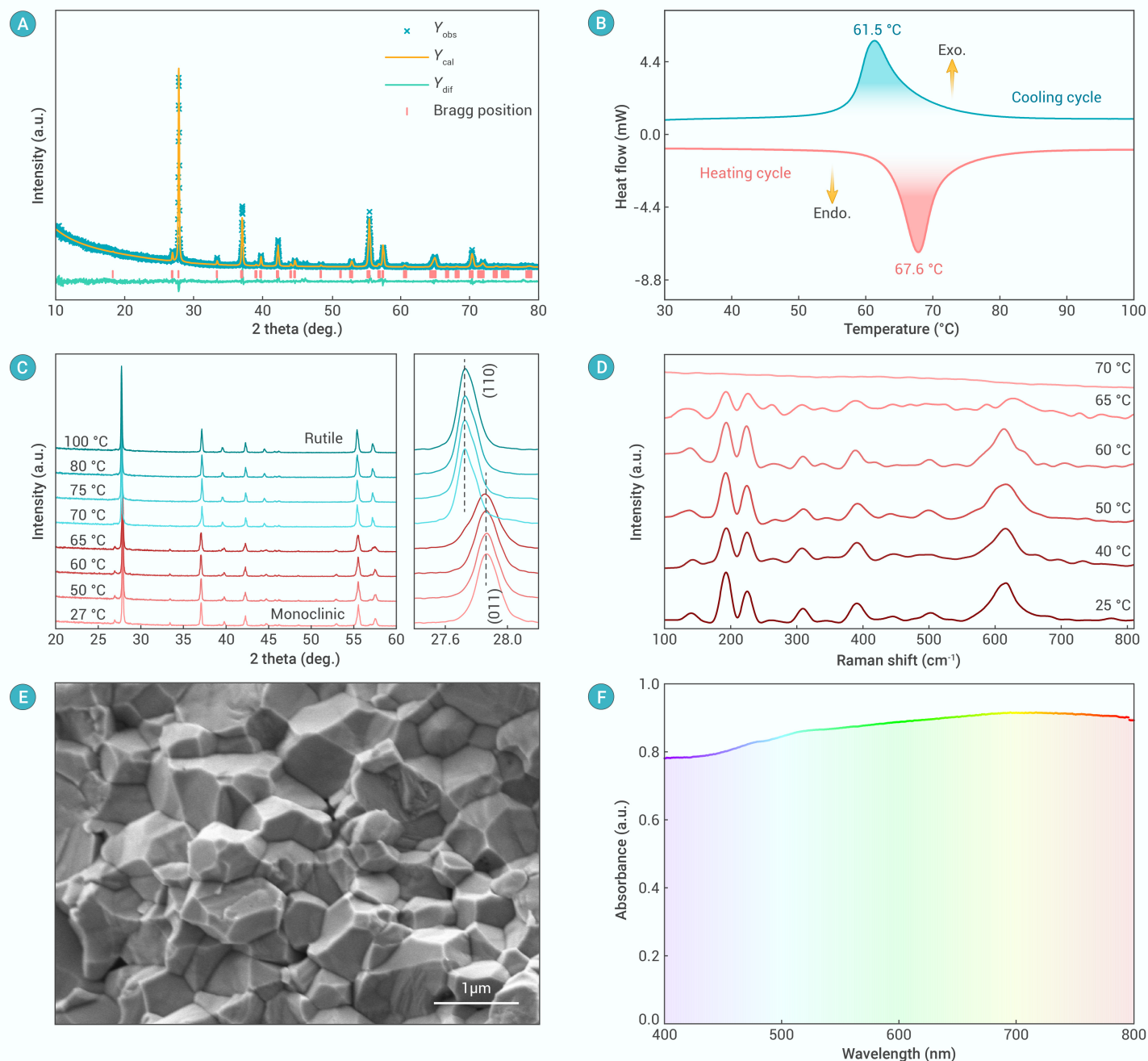


Figure 2. Phase structure characterization (A) Rietveld refinement XRD data of VO₂ ceramic. (B) DSC curves of VO₂ ceramic obtained at a heating/cooling rate of 5 °C/min under nitrogen atmosphere. (C) Variable temperature XRD diffraction patterns of VO₂ ceramic from room temperature to 100 °C. Diffraction patterns on the right shows the enlarged main peak. (D) Variable temperature Raman spectra of VO₂ ceramic. (E) SEM image of the fractured surface of VO₂ ceramic. (F) UV-vis spectrum of VO₂ ceramic.

mation ($\Delta L/L$) is gradually increased by increasing the light intensity from 100 to 3000 mW/cm², and the maximum deformation is approximately 0.15% and 0.22% for 405 and 655 nm lasers, respectively, at 3000 mW/cm². Such large photoinduced strains are comparable to the electric field induced strains in ferro/piezoelectrics.^{26–28} It is worth noting that, under the same light intensity, the VO₂ ceramic exhibits stronger deformation by 655 nm laser in comparison with 405 nm laser (Figure 3C). Besides, unlike previously reported photostrictive inorganic bulks,^{29–31} the deformation of VO₂ ceramic exhibits non-linear relationship with light intensity (Figure 3C), and an abnormal increase in deformation is observed at 2200 and 1400 mW/cm² for 405 and 655 nm laser illumination, respectively, and, at these points, the deformation process doesn't reach the stable stage within the illumination time of 30 s. Therefore, the light-on stage was extended to 60 s, and the corresponding photostriction under 655 nm laser illumination from 1000 to 2000 mW/cm² is presented in Figure S2, which clearly presents the distinctive

deformation evolution process at 1400 mW/cm². Figure 3D shows the response time of the deformation process under illumination of 655 nm laser at different intensities. It is worth noting that, when the light intensity is above 1000 mW/cm², the deformation process can be divided into a fast response stage (I) and a slow evolution stage (II), especially for 1400 mW/cm². The fast response stage within the first 5 s when light on is attributed to the general photostrictive response, which is consistent with the response time of previously reported photostrictive ceramics.^{32–34} In view of the photoinduced-phase-transition characteristic of VO₂, the slow increase after 5 s is suggested to be related to the light-triggered structural expansion of VO₂. The light intensity 1400 mW/cm² is supposed to be the threshold of the photoinduced phase transition for VO₂ ceramic when illuminated by 655 nm laser.

For most reported inorganic photostrictive materials, the photostriction is usually linearly related to the light intensity, which is also applicable to VO₂ ceramic when the illumination is below the threshold intensity (Figure 3C),

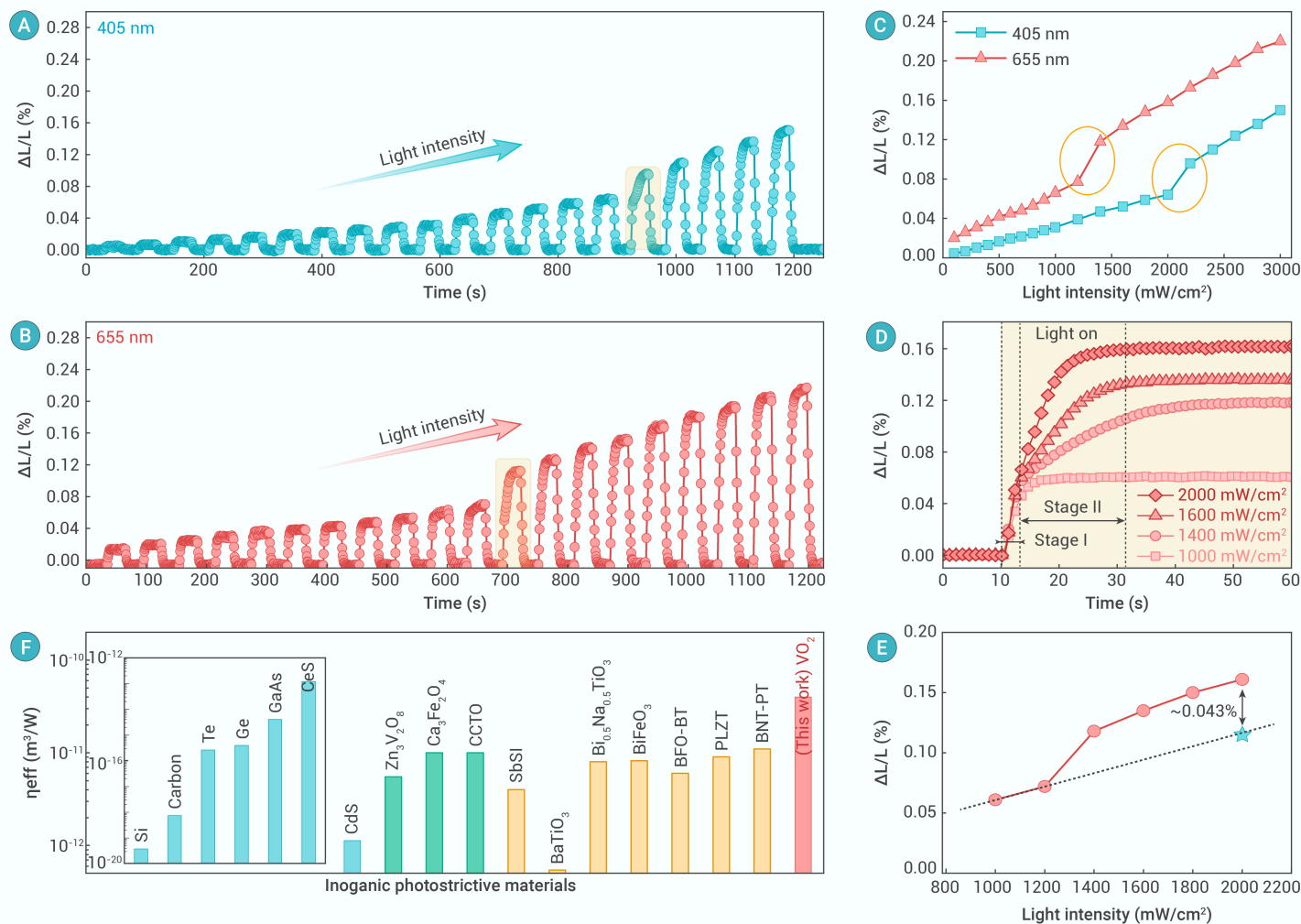


Figure 3. The photostriction of VO₂ ceramic collected under 405 nm (A) and 655 nm (B) laser illumination, respectively, with increasing the light intensity from 100 to 1000 mW/cm² with a step of 100 mW/cm², and 1000 to 3000 mW/cm² with a step of 200 mW/cm². The laser was switched on for 30 s then off for 30 s before changing the light intensity. (C) Laser-intensity-dependent photostriction of VO₂ ceramic for 405 and 655 nm lasers. (D) Comparison of the response time of the deformation of VO₂ ceramic under 655 nm laser with different light intensities. (E) Variation trend of the photostriction with the increase of light intensity for 655 nm laser. (F) Comparison of the photostrictive efficiency of some reported inorganic photostrictive materials (detailed data and references in Table S1).

such as 1400 mW/cm² for 655 nm laser. If there is no other contribution, the deformation $\Delta L/L$ should follow the predicted linear trend (dash line in Figure 3E) as lifting the light intensity. At 2000 mW/cm², the predicted $\Delta L/L$ marked by an asterisk is approximately 0.117%, which is 0.043% lower than the measured $\Delta L/L$ of 0.16%. The structure change of VO₂ from monoclinic to rutile is a first order phase transition with a volumetric change about 0.045%, which is highly consistent with the difference between the predicted value and measured value at 2000 mW/cm². Therefore, the abnormal increases (approximately 40%) in deformation observed at 2200 and 1400 mW/cm² for 405 and 655 nm laser illumination, respectively, are attributed to the phase transition of VO₂. Figure S3 gives the temperature variations of the illuminated area of VO₂ ceramic at different light intensities of 655 nm laser. Below 1000 mW/cm², the sample temperature rises almost linearly with increasing the light intensity, but an abnormal change in the temperature is observed when the light intensity is between 1000 to 1400 mW/cm², which is probably caused by the phase transition. The first-order phase transition requires a certain fraction of energy from the light illumination without lattice heating³⁵ and then breaks the linear temperature rise induced by photothermal effect. The corresponding temperature variation at this light intensity range is between 45 to 50°C, which is lower than the phase transition temperature 67.6°C (Figure 2B). Therefore, the abnormal increase in the photostriction of VO₂ above certain light intensity is caused by photoinduced phase transition rather than the thermotropic phase transition induced by photothermal effect. The detailed discussion of photothermal effect on the photostriction of VO₂ is

presented in supplemental text 1. In our previous study, the photoinduced phase transition led to the weakening or even reversal of the photoinduced shape expansion of Pb₃V₂O₈ ceramic, mainly because the cell volume of the light-induced high-temperature phase was smaller than the equilibrium phase.³⁶ Here, the cell volume of the high-temperature R-phase of VO₂ is larger than its equilibrium M-phase, therefore the photoinduced phase transition in VO₂ results in a noteworthy improvement of its photostriction.

In general, stronger illumination leads to larger deformation, therefore, to exclude the influence of sample dimension and light intensity, photostrictive efficiency η_{eff} is introduced to evaluate the photostrictive performance of bulk materials.¹⁷ The equation $\eta_{eff} = (\Delta L/L) \cdot t / I$ is used to calculate the photostrictive efficiency, where $\Delta L/L$ is the photostriction, t is the sample thickness along the illumination direction, and I is the light intensity. The average η_{eff} of VO₂ ceramic is around 7×10^{-12} and 1.7×10^{-11} m³/W for 405 and 655 nm lasers, respectively, and the maximum η_{eff} of 4×10^{-11} m³/W is obtained for 655 nm laser at 100 mW/cm². Most reported semiconductors show photostrictive efficiency in the range of 10^{-20} to 10^{-12} (Figure 3F). VO₂, as a semiconductor, exhibits much stronger photostrictive efficiency, which is comparable or even better to the popular ferroelectric photostrictive materials. The enhancement in the photostrictive efficiency of VO₂, especially for 655 nm light source, is attributed to the photoinduced structural evolution, and the underlying mechanism will be discussed through AIMD simulations in the following section.

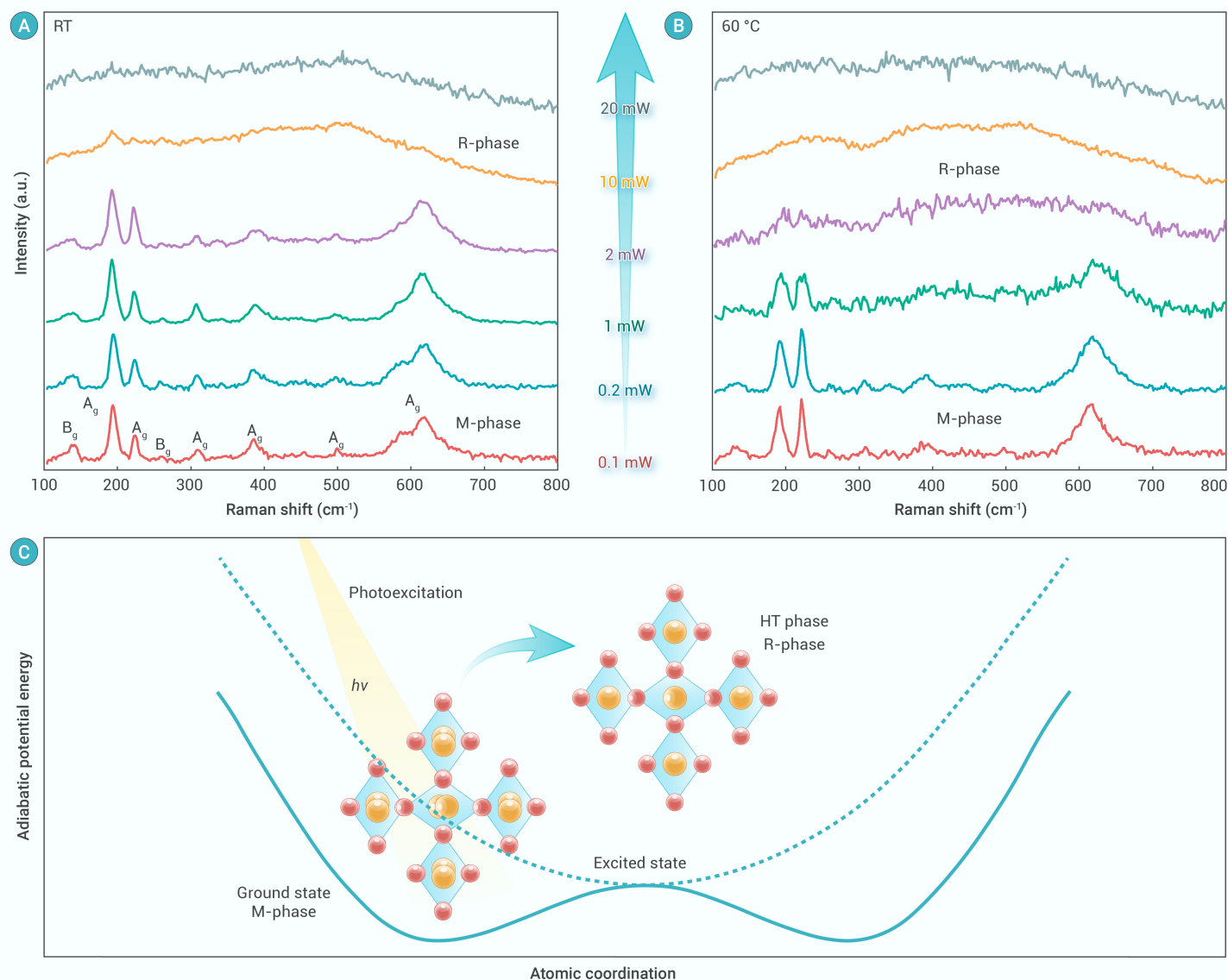


Figure 4. Raman spectra of VO₂ ceramics collected under various laser powers (0.1–20 mW, 532 nm) at room temperature (A) and 60 °C (B). (C) Potential energy surfaces of the ground state and excited states in VO₂.

Light-excited phase structural evolution

A Raman experiment was employed to evidence the photoinduced structural evolution in VO₂ ceramic. Figure 4A shows the Raman spectra of VO₂ ceramic collected at room temperature with the laser power varying from 0.1 to 20 mW. When the Raman power is below 2 mW, VO₂ ceramic exhibits typical monoclinic Raman features with vibration peaks at 140 (B_g), 194 (A_g), 223 (A_g), 262 (B_g), 308 (A_g), 340 (A_g), 388 (A_g), 495 (A_g), 614 (A_g) cm⁻¹.^{9,37–40} Under 10 mW Raman power, almost all the Raman modes of monoclinic structure disappear, expect a weak peak at 194 (A_g) cm⁻¹, indicating the phase transition to rutile structure in metallic state.^{41,42} When the Raman spectra was collected at 60 °C (Figure 4B), the photoinduced phase transition can be observed at much lower Raman powers. The Raman spectrum at 1 mW shows weakened monoclinic characteristic peaks, implying the formation of metallic domains, and the spectrum at 2 mW indicates the domination of metallic rutile phase in VO₂ ceramic. Figure 4C schematically illustrates the adiabatic potential energy surfaces (PESs) of VO₂ in the ground state and excited state as a function of the atomic coordination. Under illumination, the ground state VO₂ is excited to the Franck-Condon state (excited state), which will further relax into a sub-stable state if the laser power density is above the threshold, leading to the stabilization of the photoinduced high-temperature phase (HT phase) due to the emergence of a new energy barrier between the LT and HT phases.^{43,44}

Ab initio molecular dynamics simulations

To unravel the microscopic origin of the observed characteristics in experiments, we performed an AIMD simulations (see Methods and supplementary information for more details). The V–V bonds include long bonds and short bonds in M phase, and the V–V bonds become equal in R phase (Figure 1A). Consequently, the evolution of bond lengths stands as a symbolic representation of the M-to-R phase transition. Figure 5A displays the dynamics of V–V bond lengths under 655 nm laser wavelength, elucidating their response to varying laser fluence. Below 1.13% photoexcitation, the M-to-R phase transition cannot manifest. Beyond 1.76% photoexcitation, AIMD simulations indicate the equalization of long and short bonds. Comparatively, at 1.76% excitation, the V–V bonds exhibit more substantial oscillations than at 2.25% and 3.25% excitations (Figure 5A). Subsequently, structural relaxation was performed for the dynamic structure at 5000 fs (Figure 5B). At 2.25% and 3.25% photoexcitation, all V–V bonds achieve equality, marking a complete M-to-R phase transition. However, under 1.76% photoexcitation, a partial M-to-R phase transition is observed, as some V–V bonds fail to reach complete equalization. Therefore, we observe a sudden jump in volume between 1.76% and 2.25%, signifying the complete M-to-R phase transition (Figure 1B), which aligns well with the experimental results (Figure 3).

Furthermore, we present dynamic simulations conducted under distinct laser wavelength irradiations (Figure S4). We depict the distributions of

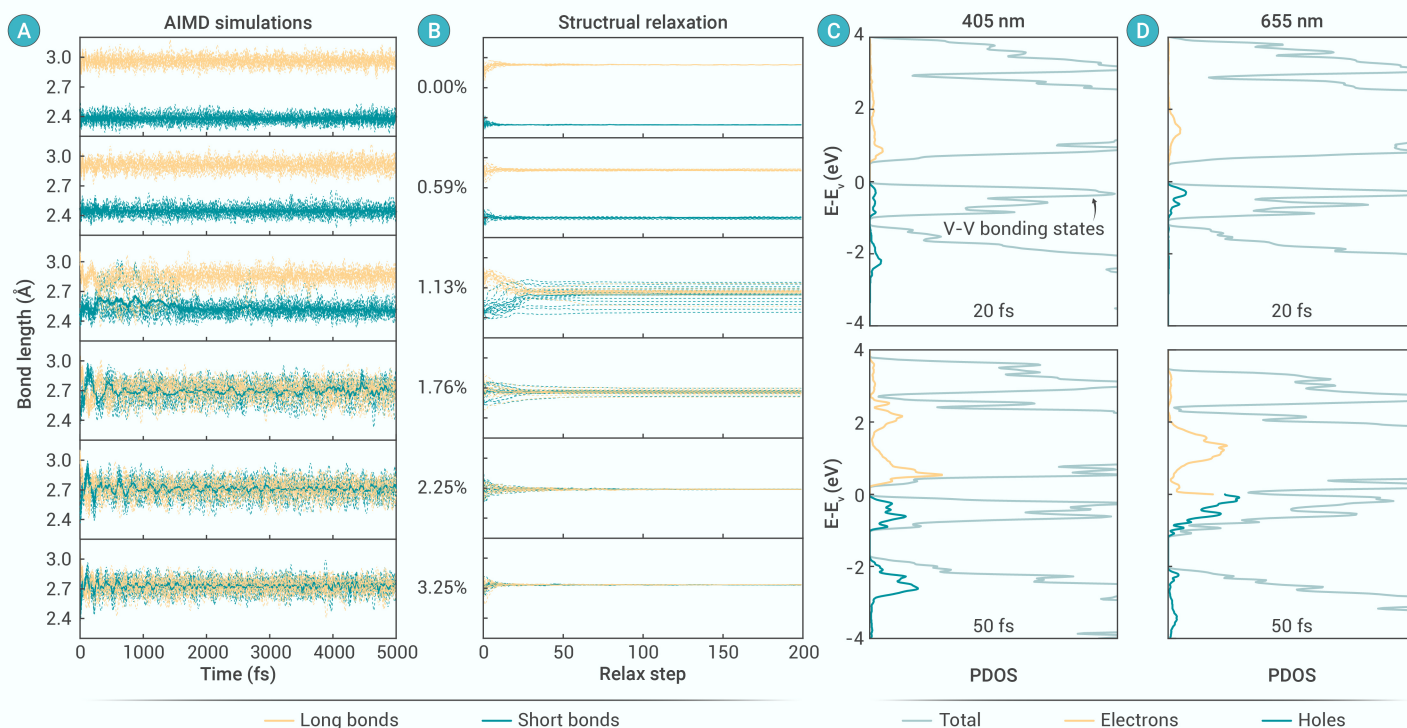


Figure 5. Structural dynamics under different electronic excitations (A) Temporal dynamics of bond lengths observed under different electronic excitations. (B) Structural relaxation of bond lengths corresponding to distinct electronic excitations. The yellow and cyan dashed lines denote the longer and shorter V-V bond lengths, respectively. The average V-V bond lengths for longer and shorter bonds are indicated by yellow and cyan solid lines. (C) The density of states (DOS) from TDDFT simulations at 20 fs and 50 fs under 405 nm laser wavelength irradiation. (D) The DOS at 20 fs and 50 fs under 655 nm laser wavelength irradiation. Gray lines represent the total DOS, and yellow (cyan) lines represent photoinduced electronic occupations (hole occupations). The V-V dimerized bonding states are highlighted by purple arrows.

photoexcited electrons and holes under 405 nm (Figure 5C) and 655 nm (Figure 5D) laser wavelengths. Notably, the distributions of photoexcited carriers under the 655 nm laser exhibit a higher degree of localization compared to those under the 405 nm laser. Specifically, the excited electrons predominantly originate from V-V dimerized bonding states when subjected to the 655 nm laser, and the holes maintain V-V dimerized bonding states, contributing to the disruption of V-V dimers (Figure 5D). An intriguing observation is the disappearance of the bandgap after photoexcitation (Figure 5D), indicative of an IMT phase transition. However, this observed distinction can be attributed to the higher photon energy associated with the 405 nm laser, resulting in electronic excitations that occupy deeper energy levels (Figure 5C). The holes predominantly occupy these deeper energy levels, which are less conducive to the breaking of V-V dimers. Consequently, the M-to-R phase transition cannot take place, and the bandgap persists after photoexcitation (Figure 5C). This nuanced insight from our dynamic simulations not only elucidates the experimental data but also sheds light on the intricate mechanisms governing the observed phase transitions. We also conducted a transient reflection (TR) spectroscopy measurement to confirm the results of AIMD simulations. The TR spectra of VO₂ ceramic at various time delays are given in Figure S5, which exhibit two photon-induced absorption (PIA) in the probe wavelength range of 400–450 nm and 550–800 nm. The stronger PIA in 550–800 nm range indicates that the photoexcited VO₂ could absorb more photons in the range of 550–800 nm and transfer to higher excited states, which also explains the better photostrictive performance of VO₂ under 655 nm illumination.

CONCLUSION

In summary, we have demonstrated the important contribution of photoinduced phase transition to the photostrictive performance of VO₂ ceramics. Above the specific light intensity threshold, the photoexcited M-to-R transition of VO₂ leads to an anomalous improvement of approximately 40% in its photostriction, leading to a large strain above 0.1%. Besides, VO₂ exhibits a more pronounced photostrictive response to 655 nm laser compared to 405 nm laser, and the light intensity threshold of the photo-triggered phase tran-

sition for 655 nm laser is also lower than that of 405 nm laser. This light-wavelength-selective photostrictive response is further elucidated by AIMD simulations. In addition, VO₂ shows an average photostrictive efficiency about $1.7 \times 10^{-11} \text{ m}^3/\text{W}$, which is orders of magnitude higher than that of other semiconductors, and is also superior to most reported ferroelectric photostrictive materials. It is worth noting that there is still space to further optimize the photostriction of VO₂ by engineering its phase transition temperature to adjust the threshold of photoexcited phase transition. The principle of using photoinduced phase transition to promote photostriction opens the door for the exploration of high-performance inorganic photostrictive materials.

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AUTHOR CONTRIBUTIONS

C.C. did most of the experiments unless stated hereafter. W.L. conducted the AIMD simulations and corresponding analysis. X.H. and L.W. helped with the preparation of VO₂ powders and ceramics. M.B. assisted in the measurement of the photostriction. F.G. helped with the AIMD simulations. X.W. contributed to the UV-vis and DSC measurement and analysis. A.T. and I.B. carried out the transient reflection spectra tests and analyzed the results. C.C. and Z.Y. conceived the main idea. J.L. directed and supervised the DFT calculations. C.C., W.L., J.L. and Z.Y. drafted and co-modified the manuscript. All authors discussed the results and revised the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND CODE AVAILABILITY

The authors declare that the main data supporting the findings of this study are available within the paper and its Supplementary information. Extra data are available on reasonable request from the corresponding author.

SUPPLEMENTAL INFORMATION

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