

Article

Probing Nanosecond-to-Microsecond Structural Dynamics by Ultrafast Transmission Electron Microscopy with Optical and Electrical Excitation

Yanqing Tong ^{1,2,†} , Siyuan Huang ^{1,2,†} , Jun Li ¹, Xiaotian Wang ^{1,2} , Huanfang Tian ¹, Huaixin Yang ^{1,2}, Shuaishuai Sun ^{1,3,*}  and Jianqi Li ^{1,2,3,*} 

- ¹ Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China; tongyanqing@iphy.ac.cn (Y.T.); huangsiyuan19@mailsucas.ac.cn (S.H.); junli@iphy.ac.cn (J.L.); wxwt@iphy.ac.cn (X.W.); hftian@iphy.ac.cn (H.T.); hxyang@iphy.ac.cn (H.Y.)
² School of Physical Sciences, University of Chinese Academy of Sciences, Beijing 100049, China
³ Songshan Lake Materials Laboratory, Dongguan 523808, China
* Correspondence: sss@iphy.ac.cn (S.S.); ljqli@iphy.ac.cn (J.L.)
† These authors contributed equally to this work.

Abstract

Time-resolved visualization of local structural dynamics driven by external fields is essential for understanding structure–property relationships in functional materials and devices. Conventional ultrafast methods primarily capture femtosecond-to-picosecond photoinduced dynamics, yet they lack real-space access to spatially inhomogeneous processes occurring at their intrinsic mesoscopic timescales that govern material and device performance—particularly electrically driven processes that closely mimic actual device operating conditions. Here, we report a multifunctional ultrafast transmission electron microscopy (UTEM) platform targeting reversible structural dynamics spanning nanoseconds to microseconds under stroboscopic multi-field excitation. Our system employs photoelectron pulses generated by nanosecond UV laser illumination as the probe, alongside optical and electric pulses as pump excitation. A unified electronic synchronization scheme based on a high-speed photodiode and a digital delay generator enables precise timing control among the optical pump, electrical pump, and photoelectron pulses across the nanosecond-to-microsecond range. Using vanadium dioxide (VO₂) as a model system, we demonstrate a combined spatiotemporal resolution with measurable signals on the order of 10 nm–10 ns, allowing real-space mapping of spatially inhomogeneous dynamics. Electrical-pump experiments further reveal Joule-heating-induced non-uniform structural phase transitions and thermal-shock-excited megahertz-range mechanical oscillations. These results establish the developed multi-field UTEM platform as a practical tool for probing local structural dynamics in functional materials under optical and electrical excitation.

Keywords: UTEM; multi-field excitation; electric pulse; nanosecond electron probe; vanadium dioxide; structural dynamics



Received: 31 May 2026

Revised: 18 June 2026

Accepted: 22 June 2026

Published: 25 June 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

In condensed matter physics and functional materials research, many key dynamic processes involve the coupled evolution of multiple microscopic degrees of freedom, including electrons, lattices, and spins, which further drive mesoscopic processes such as domain-structure reconstruction and thermal diffusion [1–3]. Their characteristic timescales

can extend from the femtosecond and picosecond regimes to the nanosecond and even microsecond regimes. In practical micro- and nanoscale devices, materials are often subjected to the combined action of multiple physical fields, such as optical, electric, thermal, and stress fields [4]. The local structural response can therefore be strongly affected by spatially inhomogeneous factors, including defects, interfaces, strain distributions, and current pathways. Representative examples include the electrical- [5–7] and optical-driven [8–10] nucleation, growth, stabilization, and motion of topological magnetic textures, which occur on nanosecond-to-microsecond timescales. Therefore, developing an experimental platform capable of directly imaging structural evolution with nanometer spatial resolution and nanosecond-to-microsecond temporal resolution is of great significance for establishing the relationship between local structural responses under external-field excitation and the macroscopic functions of devices [11].

Pump–probe techniques such as ultrafast spectroscopy and ultrafast electron diffraction have been widely employed to investigate nonequilibrium dynamic processes in materials [12]. However, these methods typically provide spatially averaged signals, making it difficult to directly resolve dynamic differences among distinct local regions. Ultrafast transmission electron microscopy (UTEM) combines the spatial resolution of transmission electron microscopy with the temporal resolution of pump–probe techniques, providing an important approach for observing real-space structural evolution during nonequilibrium processes [13–18]. However, conventional UTEM systems mainly focus on optically induced ultrafast dynamics within the femtosecond-to-picosecond timescale regime. In contrast, processes closely related to material functionality and device performance, such as domain-wall motion, thermal diffusion, and long-lived carrier relaxation, often persist over nanosecond-to-microsecond timescales [6,19–22]. Meanwhile, in practical material and device applications, electrical excitation, as one of the most commonly used driving methods, also predominantly operates within this timescale regime [23] and is highly susceptible to local factors such as defects. Therefore, extending the temporal observation window of UTEM to the nanosecond-to-microsecond regime and integrating electric pulse excitation under conditions close to realistic device operation represent important technical requirements for investigating coupled multiphysics dynamics [24,25].

Representative femtosecond UTEM systems have achieved excellent temporal resolution for optically induced ultrafast processes, but they are usually optimized for femtosecond-to-picosecond dynamics and optical excitation [15,16]. Nanosecond dynamic TEM and related time-resolved TEM approaches can access longer temporal windows, but they often emphasize single-shot or laser-driven transient processes and are not always configured for stroboscopic, device-like electrical excitation [22,25]. Recent in situ and operando electron microscopy studies have demonstrated the importance of probing electrically driven structural dynamics [23,26], but the combination of optical excitation, nanosecond electrical pumping, electronically tunable long-delay synchronization, and real-space dark-field/diffraction analysis within one UTEM platform remains technically important for investigating local device-scale dynamics [24]. Therefore, the present platform is designed to bridge this gap by providing a practical multi-field UTEM configuration for probing reversible structural dynamics from nanoseconds to microseconds under optical and electrical excitation.

To address the requirements described above, this work reports a multifunctional ultrafast transmission electron microscopy system with a broad temporal window, developed through modification of a JEM 2100Plus (JEOL Ltd., Akishima, Tokyo, Japan) transmission electron microscope. Based on the architecture of a conventional femtosecond UTEM system [27], the platform incorporates a nanosecond photoemission electron-probe mode and integrates both optical and electrical excitation schemes. In this work, vanadium

dioxide (VO₂) was selected as a model system to evaluate the spatiotemporal resolution and electrical pump–probe performance of the platform [28–30]. Through time-resolved diffraction and dark-field imaging of the photoinduced phase transition process, we verified the combined spatiotemporal resolution on the order of 10 nm–10 ns. Furthermore, by combining electric pulse excitation experiments, we demonstrate the capability of the system to track device-scale inhomogeneous structural evolution, thermal relaxation processes, and mesoscopic mechanical responses within a nanosecond-to-microsecond temporal window. These results demonstrate that the multifunctional UTEM platform with a broad temporal window can reveal local structural dynamics of functional materials driven by optical and electrical external fields in situ, and provides an effective experimental approach for real-space characterization of device-related nonequilibrium processes.

2. Results and Discussion

2.1. Construction and Synchronization Performance of Multi-Field UTEM Platform

Figure 1 illustrates the overall architecture of the multifunctional ultrafast transmission electron microscopy (UTEM) system with a broad temporal window developed at Synergetic Extreme Conditions User Facility (SECUF). The system was constructed through modification of a JEOL JEM-2100Plus transmission electron microscope. Based on the conventional femtosecond UTEM architecture (femtosecond optical pump–femtosecond electron probe), two additional operation modes were implemented: femtosecond optical pump–nanosecond electron probe [31,32] and nanosecond electrical pump–nanosecond electron probe. The present work mainly focuses on optical and electrical excitation schemes under nanosecond electron probing conditions. Through a modular design, the system can switch among optical pump, electrical pump, and combined excitation modes according to experimental requirements, thereby enabling time-resolved imaging and diffraction measurements within a temporal window ranging from nanoseconds to microseconds.

The synchronization-triggering scheme of the system uses a femtosecond laser (Spirit 1040-4, Spectra-Physics, Milpitas, CA, USA; 1040 nm, 300 fs) as the unified timing reference. The output fundamental beam is frequency-doubled by a BBO crystal to generate 520 nm green light and subsequently split into two paths by a beam splitter. One path is directly used as the optical pump pulse and introduced into the sample chamber through an optical delay line and a microscope flange window, illuminating the sample surface at an incident angle of approximately 69°. The other path is coupled into a high-speed photodiode for photoelectric conversion.

The trigger signal generated by the photodiode is fed into a digital delay generator (DG645, Stanford Research Systems, Sunnyvale, CA, USA), whose dual-channel outputs synchronously control both the generation of the probe electron beam and the electrical excitation of the sample. Channel 1 is used to trigger a nanosecond ultraviolet laser (Laser Stele-A-1, Ziyu Laser, Anshan, China; 355 nm, 15 ns). The output pulse is introduced through the laser access port between the electron gun and the TEM column to illuminate the photocathode, thereby generating a nanosecond pulsed electron beam as the probe. Channel 2 outputs electric pulses with adjustable delay, amplitude (± 5 V), and pulse width, which are transmitted to the sample through an in situ electrical holder (Fusion AX, Protochips, Morrisville, NC, USA) to realize nanosecond electrical pumping. Under this operation mode, the relative time delay between the pump pulse and the probe electron beam is primarily controlled electronically by the DG645, without relying on a mechanical delay line for long-delay scanning. Consequently, the accessible delay window can be extended from 1 ns to several tens of microseconds. In the present experiments, the upper limit is mainly determined by the 10 kHz repetition rate and the recovery time of the sample following excitation.

Figure 1 also schematically illustrates the in situ electrical sample configuration used for platform performance evaluation. The VO₂ device employed in the experiments was fabricated on a SiO₂/Si electrical chip provided by Protochips. A slit with a width of approximately 10 µm was pre-patterned at the center of the chip edge, and Au electrodes extended to both sides of the slit to enable electric pulse loading. Subsequently, a VO₂ microflake with a length of approximately 12 µm was extracted from a VO₂ single-crystal particle using focused ion beam (FIB) milling and transferred to bridge the two Au electrodes. To satisfy the requirements for transmission electron imaging and diffraction measurements, the central region of the VO₂ microflake was further thinned by FIB processing, resulting in an electron-transparent region with a final length of approximately 4.2 µm and a width of approximately 2.6 µm. The thickness of this electron-transparent region was estimated to be approximately 160 nm by EELS log-ratio thickness analysis. This device configuration enables the sample to simultaneously undergo electric pulse excitation and nanosecond electron-beam probing within the same field of view, thereby providing an experimental basis for evaluating the time-resolved real-space imaging capability of the system under electrical pump conditions.

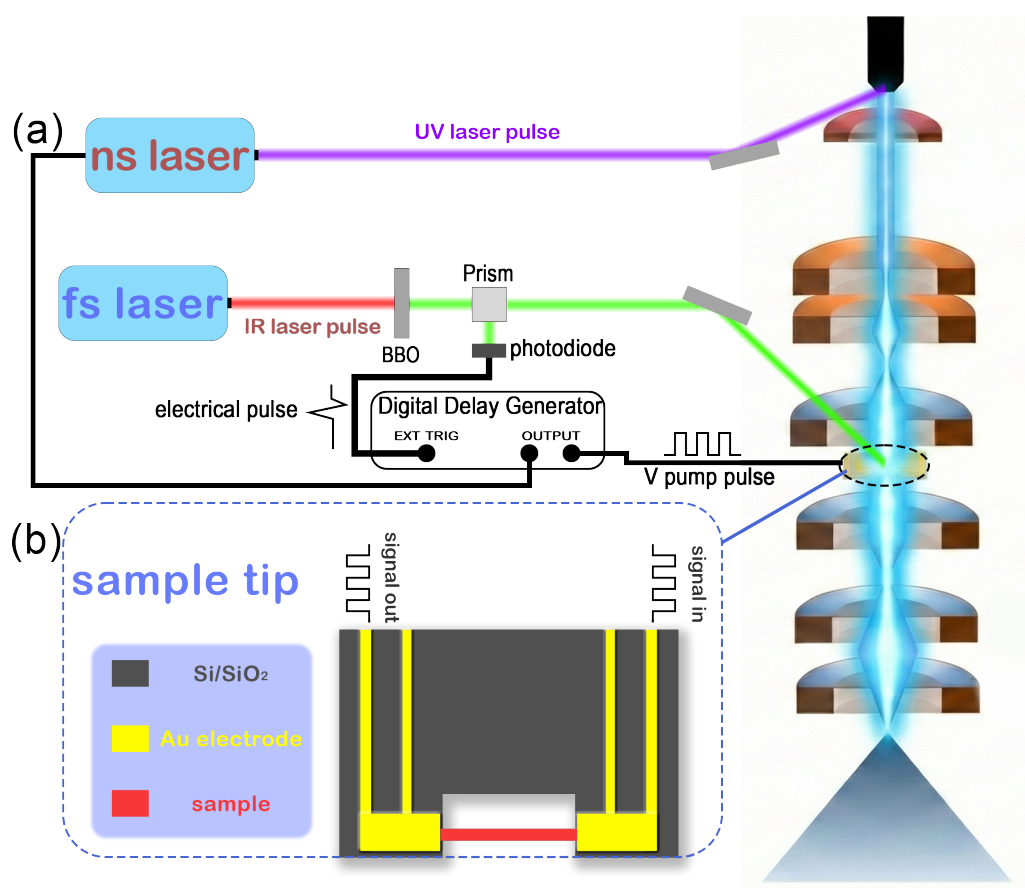


Figure 1. Schematic of the photoelectric dual-pump ultrafast transmission electron microscopy (UTEM) platform. (a) Synchronization scheme for dual-field excitation and electron-beam probing. The nanosecond laser generates the UV probe pulse for photoelectron emission, while the femtosecond laser provides the optical pump. A photodiode detects part of the femtosecond laser output and converts it into an electrical trigger, which is then used to trigger the digital delay generator and synchronize the electrical pump with the electron probe. (b) In-situ electrical-pumping specimen configuration. The VO₂ microflake is integrated between two Au electrodes on a Si/SiO₂ substrate, allowing optical excitation, electric-pulse excitation, and time-resolved electron-beam probing within the same field of view.

2.2. Spatiotemporal Dynamics and Device Performance Verification of Photoinduced Phase Transition in VO₂

After completing the architectural design and synchronization scheme of the multifunctional UTEM system with a broad temporal window, we first characterized the temporal response and real-space imaging capability of the nanosecond electron probing mode using the photoinduced insulator-to-metal phase transition in VO₂. The phase transition in VO₂ is accompanied by a structural transformation from the monoclinic M1 phase to the rutile R phase [33], which produces distinct structural contrast in both electron diffraction and dark-field imaging [34,35]. Since the characteristic timescale of the photoinduced structural response is much shorter than the nanosecond electron pulse duration employed in this work, the process can be approximated as a step response and used to extract the effective temporal resolution of the system [36–38]. Meanwhile, the phase boundaries formed during the transition provide an appropriate reference for evaluating the real-space imaging capability under nanosecond operation conditions.

In the optical-pump experiment shown in Figure 2, the VO₂ microflake was excited by 520 nm femtosecond laser pulses at a fluence of 3.06 mJ cm^{−2}, with a pump spot diameter of approximately 70 μm at the sample position, defined at the 1/e² intensity level, and a repetition rate of 10 kHz. As shown in Figure 2a, the investigated VO₂ sample exhibits a well-defined boundary in the bright-field image, and the region marked by the red circle was selected for selected-area electron diffraction (SAED) analysis. Figure 2b compares the SAED patterns acquired before optical excitation (−30 ns) and after excitation (30 ns). After excitation, the intensity of the superlattice diffraction spot (1–10), originating from the Peierls distortion of the M1 phase, is significantly suppressed, indicating a structural transition from the low-symmetry M1 phase to the high-symmetry rutile R phase. The corresponding time-resolved differential diffraction pattern shown in Figure 2c further reveals the redistribution of diffraction intensity induced by optical excitation, indicating that resolvable transient lattice structural changes occur within the selected region under the nanosecond probing window.

To quantitatively characterize the temporal response of the system, the intensity evolution of the selected diffraction spot in Figure 2b was extracted as a function of delay time and fitted using a step–Gaussian convolution model (Figure 2d). In this model, the photoinduced phase transition is treated as an instantaneous step process relative to the electron pulse duration, while the temporal profile of the probe electron pulse is approximated by a Gaussian function. The fitting result yields a full width at half maximum (FWHM) of approximately 14.6 ns for the nanosecond probe electron pulse [39], which is consistent with the pulse width of the ultraviolet excitation laser (approximately 15 ns). Figure 2d also presents the normalized intensity evolution extracted from both the entire dark-field image region and the local phase-boundary region. The consistency between the real-space and diffraction signals in their primary temporal evolution indicates that nanosecond electron diffraction and dark-field imaging exhibit good temporal correspondence under this operation mode, enabling subsequent combined analysis of phase-boundary dynamics.

In the nanosecond pulsed mode, atomic-resolution imaging is difficult to achieve because of limitations associated with electron-beam flux. However, the dynamic behavior of many condensed matter and functional materials is governed by mesoscopic domain-structure evolution, such as ferroelectric domains, magnetic domains, and structural phase domains [40–43]. Imaging these domain structures places relatively relaxed requirements on electron-beam coherence, and the contrast between different structural regions can be significantly enhanced by dark-field (DF) imaging [44–46]. Therefore, we further used VO₂ as a model system to evaluate the effective spatial resolution of this UTEM platform for real-space characterization of domain structures.

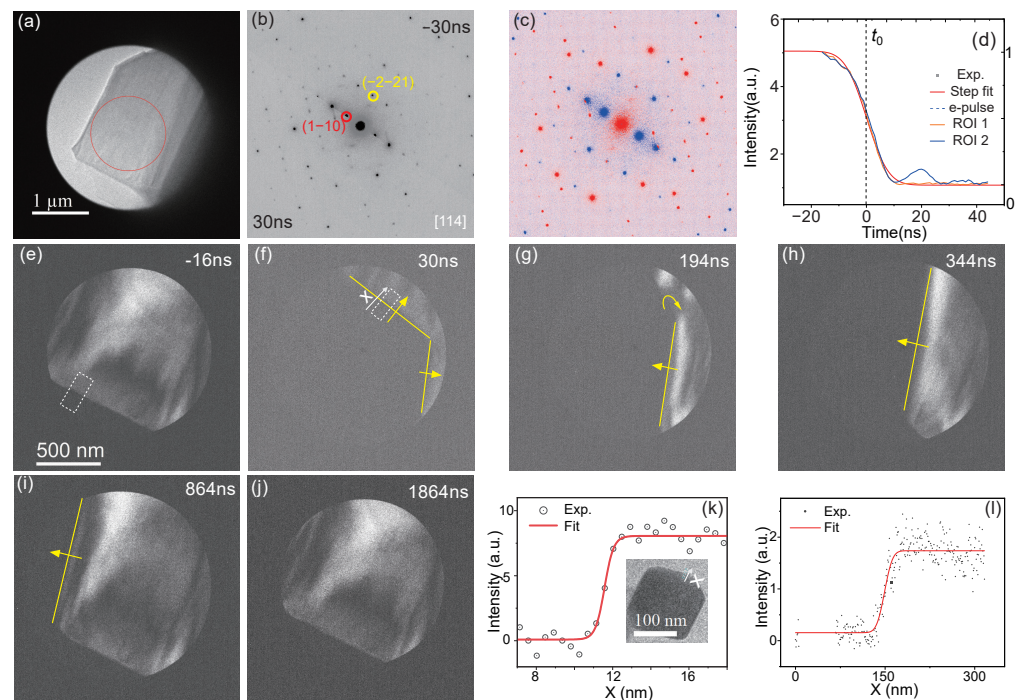


Figure 2. Ultrafast structural dynamics of VO₂ during photoinduced phase transition. (a) BF-TEM image; red circle denotes the selected area for SAED. (b) SAED patterns at −30 ns (upper) and 30 ns (lower left); red circle indicates the diffraction spot used for temporal analysis. (c) Differential diffraction map (30 ns pattern minus −30 ns pattern). (d) Intensity evolution of the diffraction spot in (b) (dots and red fit), together with normalized intensities extracted from the white dashed ROIs: ROI 1 in (e) and ROI 2 in (f), shown in orange and blue, respectively. Blue dashed line: probe electron pulse (FWHM = 14.6 ns). (e–j) Time-resolved DF-TEM sequence from −16 ns to 1864 ns showing phase recovery; yellow lines and arrows trace the transient phase front and propagation direction. (k) Edge-spread profile across a sharp TiO₂ nanoparticle edge acquired using nanosecond photoelectrons at 10 kHz; the step-Gaussian fit yields a static spatial resolution of 0.89 nm (FWHM). (l) Intensity profile along the *x*-axis (white arrow in (f)), yielding a transient resolution of 24.9 nm.

We selected the M1-phase-related superlattice diffraction spot (1–10) for time-resolved DF imaging to map the spatial distribution of the M1 phase in real space (Figure 2e–j). To further evaluate the static spatial resolving capability of the nanosecond photoelectron mode, sharp-edged TiO₂ nanoparticles were imaged at a repetition rate of 10 kHz. The edge-spread profile was fitted using a step–Gaussian convolution model, in which the nanoparticle edge was approximated as a step function and the Gaussian term represents the effective point-spread broadening. The fitted Gaussian FWHM is 0.89 nm (Figure 2k), confirming that sub-nanometer static spatial resolution can be achieved using nanosecond photoelectrons. Under the present conditions, the practical image quality is mainly limited by the available electron flux. During the transient phase transition of VO₂ (30 ns, Figure 2f), the M1 and R phases coexist, and the effective transition width at the M1/R phase boundary is approximately 24.9 nm (Figure 2l). It should be noted that this value does not represent the purely instrumental spatial resolution, but rather the effective width resulting from the convolution of the instrumental response and phase-boundary motion during the finite exposure time. Therefore, 24.9 nm should be understood as the effective spatial scale extracted from dynamic experiments rather than the limiting spatial resolution.

The time-resolved DF image sequence in Figure 2e–j further shows the emergence of pronounced phase-boundary evolution after optical excitation, followed by gradual recovery toward the initial state during structural relaxation and heat diffusion. To compare the real-space and diffraction responses, local intensity traces were extracted from the dashed-box regions indicated in Figure 2e,f. These traces exhibit step-like temporal

changes that are consistent with the diffraction-spot intensity in Figure 2d, confirming the temporal correspondence between the nanosecond dark-field contrast and diffraction response. Together, these results show that the nanosecond electron probing mode can provide both time-resolved diffraction signals and real-space tracking of mesoscopic phase-boundary evolution.

Overall, the results in Figure 2 demonstrate that the nanosecond electron probing mode developed in this work can resolve the photoinduced structural response of VO₂ on a timescale of approximately 10 ns and achieve an effective spatial resolution on the order of 10 nm in dark-field imaging mode. These results verify the feasibility of the multifunctional UTEM platform with a broad temporal window for time-resolved diffraction and real-space imaging within the nanosecond time window, providing the necessary performance basis for subsequent observations of device-scale structural dynamics under electrical pump conditions.

2.3. Non-Uniform Nucleation and Thermal Lag Under Nanosecond Electric Pulses

After characterizing the temporal response and real-space imaging capability in the nanosecond photoemission mode, we further used a VO₂ device to verify the time-resolved probing capability of this UTEM platform under electrical pump conditions. Compared with optical pumping, electric pulse excitation more closely resembles the operating conditions of practical micro- and nanoscale devices. The resulting structural response depends not only on the applied voltage, but also on the combined effects of current pathways, contact resistance, local defects, stress distribution, and substrate heat dissipation conditions [47]. Therefore, the electrical pump–nanosecond electron probe mode provides a suitable scenario for evaluating the capability of this platform to track inhomogeneous structural evolution and long-timescale thermal relaxation processes at the device scale. Figure 3a shows the bright-field image of the VO₂ device used for the electrical pump experiment, where the red circle marks the probed region used for subsequent diffraction analysis. The corresponding selected-area electron diffraction pattern is shown in Figure 3b, indicating that the sample is in the monoclinic M1 phase before excitation. In the experiment, an M1-phase-related superlattice diffraction spot (100) was selected for dark-field imaging, such that the M1-phase regions exhibit higher intensity in the dark-field images. When a local region transforms from the M1 phase to the R phase, the contribution from this superlattice diffraction is reduced, leading to a decrease in the corresponding dark-field intensity. Therefore, spatial variations in dark-field contrast can serve as a direct indicator for tracking the M1–R structural transition and the associated phase distribution [45,46,48].

At $t = 0$ ns, a square electric pulse with an amplitude of 0.7 V and a pulse width of 1000 ns was applied to the device. Figure 3d–g presents time-resolved dark-field images acquired at representative delay times, corresponding to the initial state before excitation, the transient state during electric pulse loading, the thermal-relaxation state after pulse termination, and the recovered state. Before excitation ($t = -100$ ns), the dark-field contrast of the sample largely retains the initial M1-phase distribution. After the electric pulse is applied ($t = 320$ ns), pronounced contrast changes first appear in local regions, indicating that the electrically induced structural transition does not occur synchronously across the entire field of view, but instead exhibits spatially inhomogeneous nucleation behavior [49]. This inhomogeneity may arise from variations in local current density, defects and stress concentrations introduced during FIB sample preparation, nonuniform sample thickness, and differences in thermal boundary conditions near the electrodes. As the electric pulse continues, Joule heat progressively accumulates in the device, causing more regions to reach the local temperature threshold required for the M1–R phase transition and thereby driving further expansion of the transformed regions.

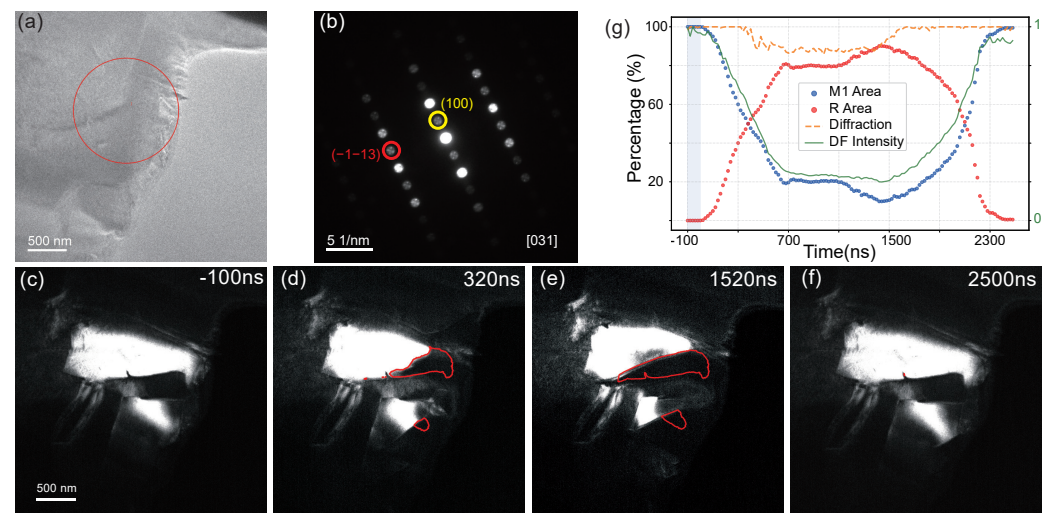


Figure 3. Nanoscale spatiotemporal dynamics of electrically driven phase transitions in VO₂. (a) BF image of the VO₂ specimen; the red circle denotes the probed area of SAED. (b) SAED pattern, with the yellow circled reflection used for dark-field (DF) imaging. (c–f) Time-resolved DF snapshots capturing the transient nucleation and growth of the R phase (red outlines). A 0.7 V, 1000 ns pulse is triggered at $t = 0$ ns, initiating the structural transformation. (g) Synchronized evolution of phase area percentages and integrated DF intensity (from the ROI in (a)) with normalized diffraction intensity (from the ROI in (b)); the shaded region indicates the reference region before the arrival of applied electrical pulse.

Figure 3g quantitatively analyzes the above process, showing the synchronized temporal evolution of the M1-phase area, R-phase area, integrated dark-field intensity, and normalized intensity of the selected diffraction spot. During electric pulse loading, the M1-phase area gradually decreases, while the R-phase area correspondingly increases. Meanwhile, the integrated dark-field intensity and diffraction-spot intensity also exhibit corresponding changes. These results indicate that both real-space dark-field imaging and reciprocal-space diffraction signals can reflect the electrically induced structural phase transition. Unlike an ideal instantaneous electric-field response, the growth of the R-phase area shows a clear delay relative to the onset of the electric pulse. This indicates that the process is mainly governed by Joule heat accumulation: the applied voltage first induces current flow and local heat generation [50], after which heat diffuses within the sample and gradually drives local regions across the phase-transition threshold, ultimately resulting in a delayed structural transition. More importantly, after the 1000 ns electric pulse ends, the transformed region does not recover immediately. Figure 3e shows that, at $t = 1520$ ns, a relatively large fraction of the sample remains in the R phase. The phase-area curves in Figure 3g also show that the R-phase fraction remains high for a period after pulse termination.

This behavior indicates that the accumulated Joule heat persists after termination of the electrical pulse, keeping local regions of the sample above the phase-transition temperature, which is estimated to be approximately 338 K [26]. Since Joule heat has accumulated in the VO₂ microflake and the surrounding electrode/substrate regions, residual heat can continue to maintain local regions above the phase-transition temperature after the pulse ends [47,51,52]. Therefore, the structural evolution after pulse termination is mainly determined by heat diffusion and thermal boundary conditions, rather than being directly controlled by the instantaneous external electric field. As heat further dissipates into the electrodes and the SiO₂/Si substrate, the local temperature gradually decreases below the phase-transition threshold. The R-phase region then starts to shrink and eventually recovers

almost completely to the initial M1-phase dark-field contrast distribution at approximately $t = 2500$ ns (Figure 3f).

It should be noted that, in electrical pump dark-field imaging, transient stress, local bending, or slight geometric tilting may also alter the Bragg condition and thereby influence the dark-field intensity. Therefore, in the phase-area analysis, we primarily identified regions based on dark-field contrast features with well-defined spatial boundaries and consistent evolution trends across consecutive time points. In addition, cross-validation was performed using the synchronized evolution of diffraction intensity and integrated dark-field intensity shown in Figure 3g. If the signal originated solely from transient tilting effects or random stress-induced contrast, its spatial distribution would generally be more diffuse and its temporal evolution would not necessarily remain consistent with the intensity evolution of the M1 superlattice diffraction spot. In contrast, the regions outlined by the red contours in this experiment exhibit continuous nucleation, expansion, and recovery processes, consistent with both the phase-area evolution and diffraction intensity changes. Therefore, the time-resolved DF image mainly reflects the electrically induced M1–R structural phase transition process.

The results shown in Figure 3 demonstrate that the multifunctional UTEM platform with a broad temporal window can achieve stable synchronization among electric pulses, nanosecond probe electron beams, and diffraction/imaging acquisition under electrical pump conditions, while enabling the tracking of device-scale inhomogeneous phase transitions and thermal relaxation processes within a nanosecond-to-microsecond temporal window. Therefore, using the VO₂ device as a model system, the results in Figure 3 verify the capability of this platform for performing time-resolved dark-field imaging and diffraction analysis under electric pulse excitation. The system enables simultaneous tracking of device-scale inhomogeneous phase transitions, Joule heat accumulation, and thermal relaxation processes within the nanosecond-to-microsecond time window, thereby providing an experimental foundation for future studies of local structural dynamics in functional-material devices.

2.4. Nanosecond Electric Pulse-Driven Coherent Acoustic Phonon

In the preceding experiments with 1000 ns electric pulses, the structural response of the VO₂ device was mainly characterized by phase-transition and relaxation processes governed by Joule heat accumulation and thermal diffusion. To further verify the capability of the multifunctional UTEM platform with a broad temporal window for probing faster electrically driven processes, the pulse width was reduced to 50 ns, and the mesoscopic dynamic responses of the sample under long- and short-pulse excitation conditions were compared. Compared with long pulses, short pulses inject energy into the sample within a much shorter timescale, while the local temperature field does not have sufficient time to reach a quasi-equilibrium state. As a result, transient thermal stress can be generated more readily, thereby exciting mechanical vibration modes of the sample.

Figure 4a,b show the spatiotemporal response of the VO₂ microflake under a 0.7 V, 1000 ns electric pulse. In Figure 4a, the three colored arrows labeled #1–3 mark the line-scan regions selected from different parts of the microflake. These arrows define both the spatial directions and the extraction ranges used for constructing the spatiotemporal intensity maps. The three maps in Figure 4b are arranged from top to bottom in the same order as arrows #1–3 in Figure 4a. In each map, the horizontal axis represents the pump–probe delay time, whereas the vertical axis represents the position along the corresponding arrow. The FFT spectrum plotted to the right of each map was calculated from the spatially averaged temporal intensity trace of that same map. Under this 0.7 V, 1000 ns pulse condition, all three regions exhibit a smooth intensity decrease followed

by gradual recovery, without pronounced periodic modulation in the spatiotemporal maps or distinct narrow-band peaks in the FFT spectra. This behavior suggests that the dark-field contrast evolution is mainly governed by Joule-heat accumulation, thermal diffusion, and slow structural relaxation associated with the M1–R phase-transition process. Figure 4c,d present the corresponding analysis under a 2.2 V, 50 ns electric pulse. In Figure 4c, the colored arrows labeled #1–3 again indicate the selected line-scan regions, and the three spatiotemporal maps in Figure 4d correspond to these arrows from top to bottom. The FFT spectrum beside each map is obtained from the spatially averaged temporal signal of the same selected region. Compared with Figure 4a,b, the maps in Figure 4d show clear periodic intensity modulations after electrical excitation. These oscillatory contrast variations indicate resolvable mesoscopic motion of the microflake rather than a purely diffusive thermal relaxation process. The corresponding FFT spectra show characteristic frequency components at approximately 14.1 MHz and 21.5 MHz. These frequency components are likely associated with mechanical resonance modes excited by transient thermal stress generated during rapid energy injection. The lower-frequency component may be related to a low-order bending-like vibration of the suspended VO₂ microflake, whereas the higher-frequency component may originate from a higher-order or more localized vibrational response.

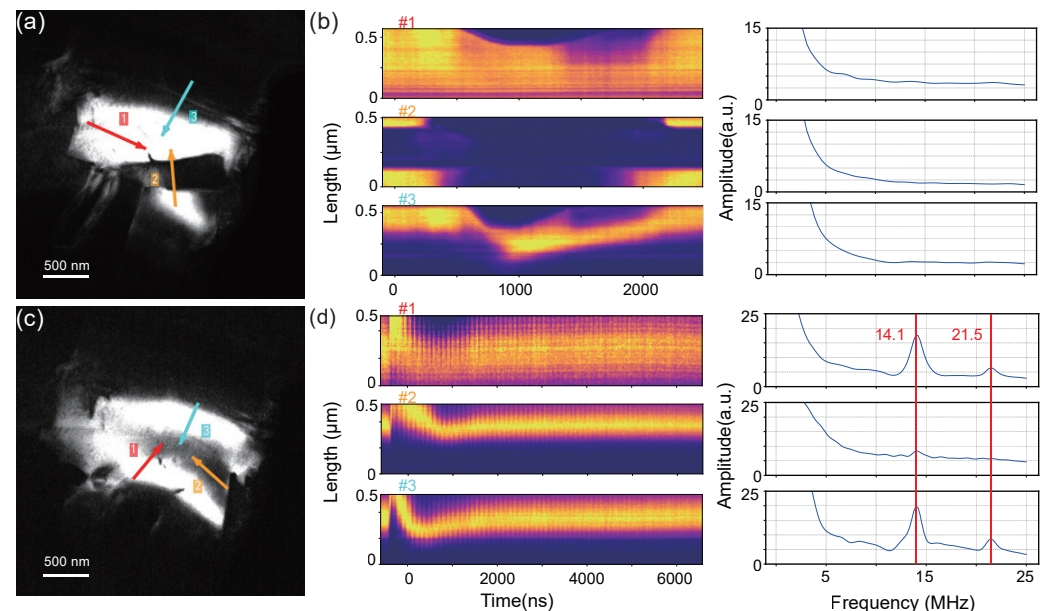


Figure 4. Nanosecond dynamics and acoustic resonances in VO₂ flakes. (a) Dark-field image under a 1000 ns, 0.7 V electric pulse. The colored arrows mark the line-profile regions for spatiotemporal analysis, and its length was manually selected according to the local dynamic region. (b) Spatiotemporal intensity maps extracted along the arrows in (a), and the corresponding FFT spectra calculated from the spatially averaged temporal signals of each pseudocolor map. The vertical axis of each pseudocolor map represents the distance along the arrow. (c) Dark-field image under a 50 ns, 2.2 V electric pulse. (d) Spatiotemporal intensity maps and spatially averaged FFT spectra extracted from the arrows in (c), showing resonance peaks at approximately 14.1 MHz and 21.5 MHz.

The difference between the responses under long and short electric pulses reflects the competition between the energy injection timescale and the thermal diffusion timescale [53]. Under long-pulse excitation, Joule heat gradually accumulates during the pulse duration and diffuses into the electrodes and substrate, causing the sample response to be dominated by thermally driven phase transitions and slow relaxation processes. In contrast, under short-pulse excitation, the local temperature and thermal stress do not have sufficient time to diffuse, and the resulting transient thermal shock can excite mesoscopic mechanical

vibrations of the microflake [23]. Therefore, Figure 4 further demonstrates the capability of this UTEM platform to characterize local dynamic processes in devices across different electric pulse timescales.

3. Conclusions

In this work, a multifunctional ultrafast transmission electron microscopy system with a broad temporal window was developed. The system integrates nanosecond photoemission electron probing together with optical and electrical pump excitation schemes. A unified electronic synchronization framework was established using a high-speed photodiode and a digital delay generator, enabling time-resolved imaging and diffraction measurements within a temporal window extending from nanoseconds to microseconds. Using VO₂ as a model system, the platform performance was characterized through its photoinduced insulator-to-metal phase transition, yielding a combined spatiotemporal resolution on the order of 10 nm–10 ns.

Further electrical pump experiments demonstrate that the platform can track device-scale inhomogeneous phase transitions, Joule heat accumulation, and thermal relaxation processes under electric pulse excitation. By comparing the responses under 1000 ns long-pulse and 50 ns short-pulse excitation conditions, the system additionally resolved MHz-scale mesoscopic vibrational features induced by transient thermal stress. These results demonstrate that the multifunctional UTEM platform with a broad temporal window can be used to investigate local structural dynamics of functional materials driven by optical and electrical external fields, and provides an effective experimental approach for real-space characterization of device-related nonequilibrium processes.

Author Contributions: Conceptualization, S.H., Y.T. and S.S.; methodology, S.H., J.L. (Jun Li) and S.S.; software, Y.T. and X.W.; validation, S.H. and J.L. (Jun Li); formal analysis, Y.T. and S.H.; investigation, S.H. and J.L. (Jun Li); resources, H.T., H.Y., S.S. and J.L. (Jianqi Li); data curation, Y.T. and S.H.; writing—original draft preparation, Y.T.; writing—review and editing, Y.T., S.H., S.S. and J.L. (Jianqi Li); visualization, Y.T. and S.H.; supervision, S.S. and J.L. (Jianqi Li); project administration, S.S. and J.L. (Jianqi Li); funding acquisition, H.Y., S.S. and J.L. (Jianqi Li). All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Key R&D Program of China (grant nos. 2024YFA1611303, 2021YFA1301502, 2024YFA1408701, and 2024YFA1408403), the National Natural Science Foundation of China (grant no. U22A6005), CAS Project for Young Scientists in Basic Research (YSBR-143), and the Scientific Instrument Developing Project of the Chinese Academy of Sciences (grant no. YJKYYQ20200055). All experiments in this work were carried out at the Synergetic Extreme Condition User Facility (SECUF, <https://cstr.cn/31123.02.SECUF> (accessed on 21 June 2026)).

Data Availability Statement: The data presented in this study are available from the corresponding authors upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Axt, V.M.; Kuhn, T. Femtosecond spectroscopy in semiconductors: A key to coherences, correlations and quantum kinetics. *Rep. Prog. Phys.* **2004**, *67*, 433–512. [[CrossRef](#)]
2. Kirilyuk, A.; Kimel, A.V.; Rasing, T. Ultrafast optical manipulation of magnetic order. *Rev. Mod. Phys.* **2010**, *82*, 2731–2784. [[CrossRef](#)]
3. Xu, C.; Zong, A. Time-domain study of coupled collective excitations in quantum materials. *npj Quantum Mater.* **2025**, *10*, 21. [[CrossRef](#)]
4. Tian, D.; Zhong, S.; Dong, J.; Zhou, S.; Liu, Z.; Chen, K.; Zhang, W.; Cao, L.; He, X.; Li, X.; et al. Room-temperature two-dimensional multiferroic metal with voltage-controllable magnetic order. *Nat. Mater.* **2026**, *25*, 956–963. [[CrossRef](#)] [[PubMed](#)]

5. Zhu, K.; Rybakov, F.N.; Wang, Z.; Gao, W.; Sun, S.; Wang, W.; Li, J.; Tian, H.; Eriksson, O.; Yang, H.; et al. Light-induced bimerons in a chiral magnet. *Nat. Commun.* **2026**, *17*, 3185. [\[CrossRef\]](#) [\[PubMed\]](#)
6. Shimojima, T.; Nakamura, A.; Yu, X.; Karube, K.; Taguchi, Y.; Tokura, Y.; Ishizaka, K. Nano-to-micro spatiotemporal imaging of magnetic skyrmion's life cycle. *Sci. Adv.* **2021**, *7*, eabg1322. [\[CrossRef\]](#) [\[PubMed\]](#)
7. Chen, X.; Yang, D.; Li, Z.; Guo, J.; Wang, H.; Hu, Y.; Kuchkin, V.M.; Savchenko, A.S.; Zhang, H.; Ding, B.; et al. Laser-induced nucleation of magnetic hopfions. *Nat. Phys.* **2026**, *22*, 736–744. [\[CrossRef\]](#)
8. Li, L.; Song, D.; Wang, W.; Kong, L.; Zhang, S.; Wang, N.; Zhang, S.; Tian, M.; Zang, J.; Liu, Y.; et al. Electrically writing a magnetic heliknoton in a chiral magnet. *Nat. Mater.* **2026**, *25*, 950–955. [\[CrossRef\]](#) [\[PubMed\]](#)
9. Tang, J.; Wu, Y.; Wang, W.; Kong, L.; Lv, B.; Wei, W.; Zang, J.; Tian, M.; Du, H. Magnetic skyrmion bundles and their current-driven dynamics. *Nat. Nanotechnol.* **2021**, *16*, 1086–1091. [\[CrossRef\]](#) [\[PubMed\]](#)
10. Wu, Y.; Jiang, J.; Kong, L.; Liu, W.; Zhang, H.; Wang, S.; Tian, M.; Du, H.; Tang, J. Current-controlled creations, deletions, and topological transformations of a single magnetic antiskyrmion in nanostructured cells. *Nat. Commun.* **2025**, *16*, 11626. [\[CrossRef\]](#) [\[PubMed\]](#)
11. Johnson, A.S.; Perez-Salinas, D.; Siddiqui, K.M.; Kim, S.; Choi, S.; Volckaert, K.; Majchrzak, P.E.; Ulstrup, S.; Agarwal, N.; Hallman, K.; et al. Ultrafast X-ray imaging of the light-induced phase transition in VO₂. *Nat. Phys.* **2023**, *19*, 215–220. [\[CrossRef\]](#)
12. Filippetto, D.; Musumeci, P.; Li, R.K.; Siwick, B.J.; Otto, M.R.; Centurion, M.; Nunes, J.P.F. Ultrafast electron diffraction: Visualizing dynamic states of matter. *Rev. Mod. Phys.* **2022**, *94*, 045004. [\[CrossRef\]](#)
13. Lobastov, V.A.; Srinivasan, R.; Zewail, A.H. Four-dimensional ultrafast electron microscopy. *Proc. Natl. Acad. Sci. USA* **2005**, *102*, 7069–7073. [\[CrossRef\]](#) [\[PubMed\]](#)
14. Zewail, A.H. Four-dimensional electron microscopy. *Science* **2010**, *328*, 187–193. [\[CrossRef\]](#) [\[PubMed\]](#)
15. LaGrange, T.; Cattaneo, P.; Barwick, B.; Flannigan, D.J.; Weissenrieder, J.; Carbone, F. Laser-driven ultrafast transmission electron microscopy. *Nat. Rev. Methods Primers* **2025**, *5*, 61. [\[CrossRef\]](#)
16. Zhu, C.; Zheng, D.; Wang, H.; Zhang, M.; Li, Z.; Sun, S.; Xu, P.; Tian, H.; Li, Z.; Yang, H.; et al. Development of analytical ultrafast transmission electron microscopy based on laser-driven Schottky field emission. *Ultramicroscopy* **2020**, *209*, 112887. [\[CrossRef\]](#) [\[PubMed\]](#)
17. Aseyev, S.A.; Mironov, B.N.; Poydashev, D.G.; Ryabov, E.A.; Miller, R.J.D.; Zheng, L.; Zhang, M.; Ischenko, A.A. High spatiotemporal resolution transmission electron microscopy and diffraction: Progress from subnanosecond laser-induced structural dynamics to femtosecond quantum tomography. *Nano Today* **2025**, *61*, 102638. [\[CrossRef\]](#)
18. Wang, W.; Sun, S.; Li, J.; Zheng, D.; Huang, S.; Tian, H.; Yang, H.; Li, J. Capturing the non-equilibrium state in light-matter-free-electron interactions through ultrafast transmission electron microscopy. *Chin. Phys. B* **2023**, *33*, 010701. [\[CrossRef\]](#)
19. Alcorn, F.M.; Jain, P.K.; van der Veen, R.M. Time-resolved transmission electron microscopy for nanoscale chemical dynamics. *Nat. Rev. Chem.* **2023**, *7*, 256–272. [\[CrossRef\]](#) [\[PubMed\]](#)
20. Grigoriev, A.; Do, D.H.; Kim, D.M.; Eom, C.B.; Adams, B.; Dufresne, E.M.; Evans, P.G. Nanosecond domain wall dynamics in ferroelectric Pb(Zr,Ti)O₃ thin films. *Phys. Rev. Lett.* **2006**, *96*, 187601. [\[CrossRef\]](#) [\[PubMed\]](#)
21. Gao, L.; Hu, Z.; Lu, J.; Liu, H.; Ni, Z. Defect-related dynamics of photoexcited carriers in 2D transition metal dichalcogenides. *Phys. Chem. Chem. Phys.* **2021**, *23*, 8222–8235. [\[CrossRef\]](#) [\[PubMed\]](#)
22. Sinha, S.K.; Khammari, A.; Picher, M.; Roulland, F.; Viart, N.; LaGrange, T.; Banhart, F. Nanosecond electron pulses in the analytical electron microscopy of a fast irreversible chemical reaction. *Nat. Commun.* **2019**, *10*, 3648. [\[CrossRef\]](#) [\[PubMed\]](#)
23. Durham, D.B.; Gage, T.E.; Horn, C.P.; Ma, X.; Liu, H.; Arslan, I.; Guha, S.; Phatak, C. Nanosecond structural dynamics during electrical melting of charge density waves in 1T-TaS₂. *Phys. Rev. Lett.* **2024**, *132*, 226201. [\[CrossRef\]](#) [\[PubMed\]](#)
24. Ji, S.; Chen, L.; Fu, X. In-situ ultrafast transmission electron microscopy: Advancing ultrafast dynamics research under multi-field coupling at the nanoscale. *Chin. Phys. Lett.* **2025**, *42*, 016101. [\[CrossRef\]](#)
25. LaGrange, T.; Campbell, G.H.; Reed, B.W.; Taheri, M.; Pesavento, J.B.; Kim, J.S.; Browning, N.D. Nanosecond time-resolved investigations using the in situ of dynamic transmission electron microscope (DTEM). *Ultramicroscopy* **2008**, *108*, 1441–1449. [\[CrossRef\]](#) [\[PubMed\]](#)
26. Huang, S.; Sun, S.; Shi, Y.; Wang, W.; Zhu, C.; Tian, H.; Yang, H.; Li, J.; Li, J. Electrically steered conduction topologies and period-doubling phase dynamics in VO₂. *arXiv* **2026**, arXiv:2604.19329. [\[CrossRef\]](#)
27. Gao, W.; Sun, S.; Zhang, Y.; Zhu, K.; Wang, W.; Li, J.; Tian, H.; Yang, H.; Li, Z.; Li, J. Stacking order regulated coherent shear phonons in octahedral MoTe₂ revealed by ultrafast electron microscopy. *ACS Nano* **2025**, *19*, 19622–19634. [\[CrossRef\]](#) [\[PubMed\]](#)
28. Morin, F.J. Oxides which show a metal-to-insulator transition at the Neel temperature. *Phys. Rev. Lett.* **1959**, *3*, 34–36. [\[CrossRef\]](#)
29. Wegkamp, D.; Stähler, J. Ultrafast dynamics during the photoinduced phase transition in VO₂. *Prog. Surf. Sci.* **2015**, *90*, 464–502. [\[CrossRef\]](#)
30. Atkin, J.M.; Berweger, S.; Chavez, E.K.; Raschke, M.B.; Cao, J.; Fan, W.; Wu, J. Strain and temperature dependence of the insulating phases of VO₂ near the metal-insulator transition. *Phys. Rev. B* **2012**, *85*, 020101. [\[CrossRef\]](#)

31. Sun, S.; Li, Z.; Li, Z.-A.; Xiao, R.; Zhang, M.; Tian, H.; Yang, H.; Li, J. Cooperative inter- and intra-layer lattice dynamics of photoexcited multi-walled carbon nanotubes studied by ultrafast electron diffraction. *Nanoscale* **2018**, *10*, 7465–7471. [[CrossRef](#)] [[PubMed](#)]
32. Wang, W.; Sun, S.; Gao, W.; Zhu, K.; Tian, H.; Yang, H.; Li, J. Ultrafast laser-induced anisotropic structural dynamics of five-fold twinned silver nanowires. *Phys. Rev. Mater.* **2026**, *10*, 046002. [[CrossRef](#)]
33. Goodenough, J.B. The two components of the crystallographic transition in VO₂. *J. Solid State Chem.* **1971**, *3*, 490–500. [[CrossRef](#)]
34. Cavalleri, A.; Dekorsy, T.; Chong, H.H.W.; Kieffer, J.C.; Schoenlein, R.W. Evidence for a structurally-driven insulator-to-metal transition in VO₂: A view from the ultrafast timescale. *Phys. Rev. B* **2004**, *70*, 161102. [[CrossRef](#)]
35. Kim, Y.-J.; Lee, Y.; Kim, K.; Kwon, O.-H. Light-induced anisotropic morphological dynamics of black phosphorus membranes visualized by dark-field ultrafast electron microscopy. *ACS Nano* **2020**, *14*, 11383–11393. [[CrossRef](#)] [[PubMed](#)]
36. Xu, C.; Jin, C.; Chen, Z.; Lu, Q.; Cheng, Y.; Zhang, B.; Qi, F.; Chen, J.; Yin, X.; Wang, G.; et al. Transient dynamics of the phase transition in VO₂ revealed by mega-electron-volt ultrafast electron diffraction. *Nat. Commun.* **2023**, *14*, 1265. [[CrossRef](#)] [[PubMed](#)]
37. Morrison, V.R.; Chatelain, R.P.; Tiwari, K.L.; Hendaoui, A.; Bruhacs, A.; Chaker, M.; Siwick, B.J. A photoinduced metal-like phase of monoclinic VO₂ revealed by ultrafast electron diffraction. *Science* **2014**, *346*, 445–448. [[CrossRef](#)] [[PubMed](#)]
38. Li, J.; Wu, L.; Yang, S.; Jin, X.; Wang, W.; Tao, J.; Boatner, L.; Babzien, M.; Fedurin, M.; Palmer, M.; et al. Direct detection of V–V atom dimerization and rotation dynamic pathways upon ultrafast photoexcitation in VO₂. *Phys. Rev. X* **2022**, *12*, 021032. [[CrossRef](#)]
39. Ge, Q.; Gao, W.; Yang, D.; Zheng, D.; Zhu, K.; Li, J.; Tian, H.; Li, J.; Yang, H.; Sun, S. Grating-enhanced transverse broadening for direct measurement of electron pulse duration in an ultrafast electron microscope. *Rev. Sci. Instrum.* **2026**, *97*, 053702. [[CrossRef](#)] [[PubMed](#)]
40. Catalan, G.; Seidel, J.; Ramesh, R.; Scott, J.F. Domain wall nanoelectronics. *Rev. Mod. Phys.* **2012**, *84*, 119–156. [[CrossRef](#)]
41. Yamada, R.; Kurebayashi, D.; Fujishiro, Y.; Okumura, S.; Nakamura, D.; Yasin, F.S.; Nakajima, T.; Yokouchi, T.; Kikkawa, A.; Taguchi, Y.; et al. Emergent electric field induced by dissipative sliding dynamics of domain walls in a Weyl magnet. *Nat. Phys.* **2026**, *22*, 239–244. [[CrossRef](#)]
42. Gomes, M.M.; Silva, A.S.; Vilarinho, R.; Moreira, J.A.; Mihalik, M., Jr.; Mihalik, M.; Davies, C.S.; Kirilyuk, A.; Paixão, J.A.; Carpenter, M.A. Magnetic and structural domain walls dynamics in a two magnetic sublattice system. *Phys. Rev. B* **2025**, *112*, 224401. [[CrossRef](#)]
43. Zhang, J.; Wang, L.; Lü, J.; Wang, Z.; Wu, H.; Zhu, G.; Wang, N.; Xue, F.; Zeng, X.; Zhu, L.; et al. Interlayer reconstruction phase transition in van der Waals materials. *Nat. Mater.* **2025**, *24*, 369–376. [[CrossRef](#)] [[PubMed](#)]
44. Danz, T.; Domrose, T.; Ropers, C. Ultrafast nanoimaging of the order parameter in a structural phase transition. *Science* **2021**, *371*, 371–374. [[CrossRef](#)] [[PubMed](#)]
45. Cheng, S.; Lee, M.-H.; Tran, R.; Li, Z.; Xing, Y.; Wang, J.; Jariwala, D.; Zhu, Y. Inherent stochasticity during insulator–metal transition in VO₂. *Proc. Natl. Acad. Sci. USA* **2021**, *118*, e2105895118. [[CrossRef](#)] [[PubMed](#)]
46. Cheng, S.; Lee, M.-H.; Li, X.; Zhang, C.; Tran, R.; Li, Z.; Jariwala, D.; Zhu, Y. Operando characterization of conductive filaments during resistive switching in Mott VO₂. *Proc. Natl. Acad. Sci. USA* **2021**, *118*, e2013676118. [[CrossRef](#)] [[PubMed](#)]
47. Sood, A.; Shen, X.; Shi, Y.; Kumar, S.; Park, S.J.; Zajac, M.; Sun, Y.; Chen, L.-Q.; Ramanathan, S.; Wang, X.; et al. Universal phase dynamics in VO₂ switches revealed by ultrafast operando diffraction. *Science* **2021**, *373*, 352–355. [[CrossRef](#)] [[PubMed](#)]
48. Domröse, T.; Fernandez, N.; Eckel, C.; Leuthner, G.T.; Mathey, A.C.; Schürmann, R.; Späth, A.; Müller-Caspary, K.; Müller, E.; Sangiovanni, G.; et al. Nanoscale operando imaging of electrically driven charge-density-wave phase transitions. *Nano Lett.* **2024**, *24*, 12476–12485. [[CrossRef](#)] [[PubMed](#)]
49. O’Callahan, B.T.; Jones, A.C.; Park, J.H.; Cobden, D.H.; Atkin, J.M.; Raschke, M.B. Inhomogeneity of the ultrafast insulator-to-metal transition dynamics of VO₂. *Nat. Commun.* **2015**, *6*, 6849. [[CrossRef](#)] [[PubMed](#)]
50. Li, D.; Sharma, A.A.; Gala, D.K.; Shukla, N.; Paik, H.; Datta, S.; Schlom, D.G.; Bain, J.A.; Skowronski, M. Joule heating-induced metal-insulator transition in epitaxial VO₂/TiO₂ devices. *ACS Appl. Mater. Interfaces* **2016**, *8*, 12908–12914. [[CrossRef](#)] [[PubMed](#)]
51. Liao, G.M.; Chen, S.; Fan, L.L.; Chen, Y.L.; Wang, X.Q.; Ren, H.; Zhang, Z.M.; Zou, C.W. Dynamically tracking the Joule heating effect on the voltage induced metal-insulator transition in VO₂ crystal film. *AIP Adv.* **2016**, *6*, 045014. [[CrossRef](#)]
52. Stone, G.; Shi, Y.; Jerry, M.; Stoica, V.; Paik, H.; Cai, Z.; Schlom, D.G.; Engel-Herbert, R.; Datta, S.; Wen, H.; et al. In-operando spatiotemporal imaging of coupled film-substrate elastodynamics during an insulator-to-metal transition. *Adv. Mater.* **2024**, *36*, 2312673. [[CrossRef](#)] [[PubMed](#)]
53. Yin, J.; Lan, L.; Zhang, Y.; Ni, H.; Tan, Y.; Zhang, M.; Bai, Y.; Cheng, J.X. Nanosecond-resolution photothermal dynamic imaging via MHz digitization and match filtering. *Nat. Commun.* **2021**, *12*, 7097. [[CrossRef](#)] [[PubMed](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.