

RESEARCH ARTICLE | JANUARY 27 2025

Influence of substrate orientation and pre-annealing treatment on the metal–insulator transition in V_2O_3 films: Insights from Al_2O_3 r , a , c , and m -plane substrates

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J. Appl. Phys. 137, 045302 (2025)

<https://doi.org/10.1063/5.0245429>



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Cite as: J. Appl. Phys. **137**, 045302 (2025); doi: [10.1063/5.0245429](https://doi.org/10.1063/5.0245429)

Submitted: 26 October 2024 · Accepted: 5 January 2025 ·

Published Online: 27 January 2025



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ABSTRACT

We investigate the structural and metal-insulator transition (MIT) behavior of epitaxial V_2O_3 films fabricated by reactive direct current magnetron sputtering on r , a , c , and m -plane Al_2O_3 substrates, in both as-received and annealed states. Characterization of MIT of the V_2O_3 films grown on annealed substrates demonstrated significant changes in observed MIT properties, i.e., r -plane films showed ≈ 2 order increase in transition magnitude, m -plane ≈ 6 orders, and c -plane films exhibited a reduction of ≈ 3 orders, compared to un-annealed substrates, whereas for V_2O_3 on annealed a -plane, it revealed a shift in the transition to higher values, with reduction in hysteresis width. Structural characterization conducted via x-ray diffraction and atomic force microscopy revealed a reduction in out-of-plane compressive strain for annealed substrates, along with decreased lateral grain size. Additionally, the correlation between the V_2O_3 MIT and its underlying structural phase transition was verified by temperature-dependent x-ray diffraction analysis. These findings highlight the role of substrate orientation and pre-annealing in tuning the MIT behavior of V_2O_3 films grown on the Al_2O_3 substrate.

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I. INTRODUCTION

Vanadium oxides, characterized by multiple oxidation states and a wide range of crystalline structures, exhibit a remarkable variety of physical and chemical properties. This versatility makes them technologically important and a valuable platform for fundamental research. Vanadium sesquioxide (V_2O_3) films have recently been shown to be promising candidates for various applications, including thermal sensors, optical switches, resistive switching devices, bolometers, sensors, hybrid magnetic heterostructures, MEMS, and energy storage systems.^{1–8} V_2O_3 is characterized by its manifestation of Mott-Hubbard physics⁹ and undergoes a first-order structural phase transition (SPT) from a high-temperature rhombohedral paramagnetic metallic state to a low-temperature monoclinic anti-ferromagnetic insulating state.^{1,9,10} Extensive investigations have been conducted to study the relationship between the metal-insulator transition (MIT)

observed in V_2O_3 and its structural dynamics. Studies have explored various factors, such as doping, the presence of oxygen vacancies and/or vanadium interstitials, film thickness modulation, substrate selection, strain states, and subsequent interface characteristics, in addition to the fabrication methodology.^{9–11} These multifaceted approaches have demonstrated the capability to exert significant control over the electrical characteristics of V_2O_3 films, offering insights into the underlying mechanisms governing their behavior.

Considerable effort has been directed toward understanding the impact of doping on the MIT characteristics of V_2O_3 . With tungsten (W) doping, titanium (Ti) doping, or vanadium (V) vacancies, the transition temperature (T_{MIT}) tends to shift toward lower temperatures until the insulating phase is completely suppressed, mirroring observations in V-vacancy-mediated MIT scenarios. The introduction of higher valence dopants, such as electron donors, weakens the V–V pairs, inducing lattice expansion

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that disrupts the Peierls-paired vanadium ions, consequently reducing T_{MIT} . Conversely, chromium (Cr) doping exhibits contrasting behavior, wherein the metallic state is suppressed due to Cr's tendency to foster excess oxygen in the films,¹² akin to those containing oxygen interstitials within Frenkel pairs.^{12,13}

For electronically correlated materials system, lattice strain frequently induces profound effects on their physical characteristics.^{11,14,15} This observation offers a compelling approach to manipulating the physical properties of materials through the introduction of lattice strain. Particularly, fabricating materials as hetero-epitaxial thin films represents a practical approach to attain substantial lattice strain, as thin films typically experience significant strain originating from the substrate. From the perspective of device application, strain engineering in thin films emerges as a highly significant and relevant area of research. The significance of this communication lies in investigating the impact of utilizing different oriented substrates of sapphire in pre-annealed and un-annealed states, as they can introduce diverse strain states resulting from varying degrees of lattice mismatch and surface morphology. Additionally, the study provides results on the impact of the substrate orientation and pre-treatment on the metal-insulator characteristics of V_2O_3 film.

II. EXPERIMENTAL

The V_2O_3 thin films were fabricated onto $10 \times 10 \text{ mm}^2$ Al_2O_3 substrates, with r , a , c , and m -plane surface orientations, by reactive direct current magnetron sputtering (r -dcMS) from a circular 3-in. vanadium (V) target using a custom-built sputtering chamber.¹⁶ Prior to deposition, the chamber was held at a base pressure of 10^{-6} Pa, and the substrates were pre-baked at 600°C for 30 min. For deposition, Ar was used as the working gas along with O_2 as a reactive gas. During growth, throttle valves were adjusted to stabilize the growth pressure of 0.7 Pa. The flow rates $q_{Ar} = 40 \text{ sccm}$ and $q_{O_2} = 0.85 \text{ sccm}$ were set using mass flow controllers. During deposition, the substrates were held at 600°C . After deposition, the films were cooled down *in situ* under vacuum. The growth parameters were chosen according to previous investigations to obtain a well defined metal-insulator transition.⁹

Two distinct approaches were utilized for deposition of V_2O_3 , deposition on an un-annealed Al_2O_3 substrate and those which were pre-annealed (baked) at 1200°C for 12 h in air. The annealing of substrates was carried out in a Heraeus D-6450 Hanau resistive furnace. For annealing, an alumina tube of diameter $\approx 20 \text{ mm}$ was placed in a furnace and allowed to pre-heat for a few hours until the temperature was stabilized. The sample was then inserted into the alumina tube for annealing.

The structural properties of the films were characterized using atomic force microscopy, x-ray reflectivity (XRR), and x-ray diffraction (XRD) measurements. X-ray measurements were performed using a Panalytical X'pert diffractometer ($CuK\alpha_1$, $1.54 \text{ \AA}$). A detailed description of x-ray diffraction analysis is provided in our previous works.⁹ The structural phase transition of the V_2O_3 films was characterized by temperature-dependent x-ray diffraction implemented on the same system using a liquid nitrogen cooled Anton-Parr non-ambient stage with a graphite dome. The surface morphological properties of the films were investigated by atomic

force microscopy (AFM) (Park System PSIA XE-100) in contact mode. The metal-insulator transition of the films was characterized by temperature-dependent resistance measurements in a custom built helium cooled cryostat in vacuum. To facilitate the electrical characterization, co-planar contacts of 100 nm thick Au with a 5 nm thick Cr wetting layer were deposited along the edges of the films using electron-beam evaporation.

III. RESULTS AND DISCUSSION

A. X-ray diffraction analysis

XRR analysis was performed on the films in order to determine their thickness. A typical XRR scan and fit for a V_2O_3 film on a -plane Al_2O_3 is shown in Fig. 1, with a thickness of $\approx 47 \pm 2.3 \text{ nm}$. The results show clear Kiessig interference fringes revealing the well defined thickness of the V_2O_3 with low roughness. The thickness and roughness values for the films were determined from fitting of the XRR scans using the X'Pert reflectivity software.

The crystallographic structure of the V_2O_3 films was investigated by x-ray diffraction analysis. Figure 2 shows x-ray diffraction scans at room temperature for the V_2O_3 thin films deposited on r , a , c , and m -plane Al_2O_3 . Each graph shows a comparison of the x-ray diffraction scans for films on un-annealed and annealed substrates. All films, excluding the film grown on the a -plane substrate, showed strong peaks corresponding to the relevant lattice direction illustrating a highly textured or epitaxial film growth. The V_2O_3 peak for the film grown on c -plane Al_2O_3 shows Laue oscillations extending on both sides of the peak indicating a full crystallographic coherence throughout the film thickness. Our previous works have documented the epitaxial nature of the V_2O_3 films grown on c - and r -plane Al_2O_3 studied by XRD and reciprocal space mapping. However, to scrutinize the in-plane epitaxial nature

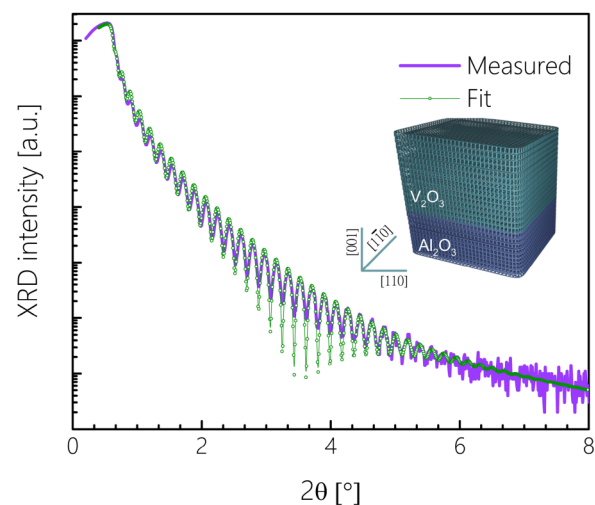


FIG. 1. X-ray reflectivity scan of a 47 nm thick V_2O_3 film grown on annealed a -plane Al_2O_3 substrate. The solid line represents the measured data and the line with open circles represents the fitting.

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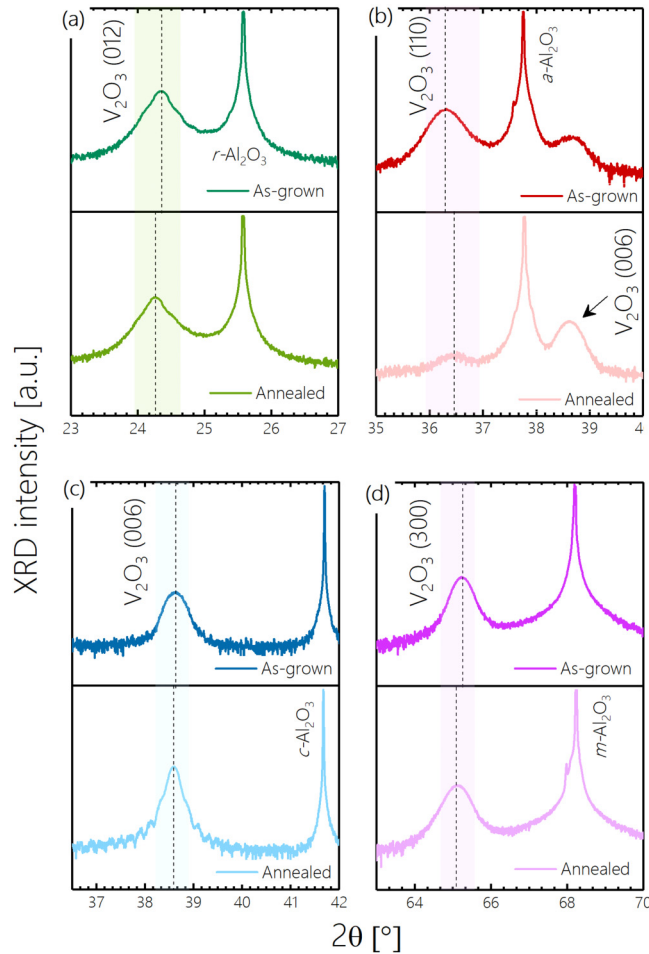


FIG. 2. X-ray diffraction scans at room temperature of V_2O_5 films grown on both un-annealed and annealed substrates. Graphs (a)–(d) show scans for films grown on r , a , c , and m -plane Al_2O_3 substrates, respectively. Dotted lines indicate the relevant V_2O_5 peak position for un-annealed and annealed substrates to highlight their shift in position. The standard 2θ peak position (according to Reference code#: 00-034-0187 [Nat. Bur. Stand. (U.S.) Monogr. 25, 20, 108, 1983]) for $r(012)$, $a(110)$, $c(006)$, and $m(300)$ -oriented V_2O_5 are 24.314° , 36.231° , 38.514° , and 65.195° , respectively.

of the V_2O_5 film with Al_2O_3 -substrate, phi-scans were recorded for the V_2O_5 (1 0 4) reflection deposited on to c - and a -plane sapphire, whereas reciprocal space map conducted on film deposited on m -sapphire and are presented in Fig. S1 in the [supplementary material](#). For instance, in the case of V_2O_5 on c -plane sapphire, the phi scan showed that three high-intensity peaks and three low-intensity peaks rotated 60° to that of high-intensity peaks are observed at $\chi = 38.25^\circ$. The high-intensity peaks of V_2O_5 align well with the substrate peaks, i.e., Al_2O_3 (0 0 0 6), and arise from epitaxial grains.

As can be seen from Fig. 2(b), XRD analysis of V_2O_5 films grown on a -plane Al_2O_3 substrate reveals two distinct peaks. The

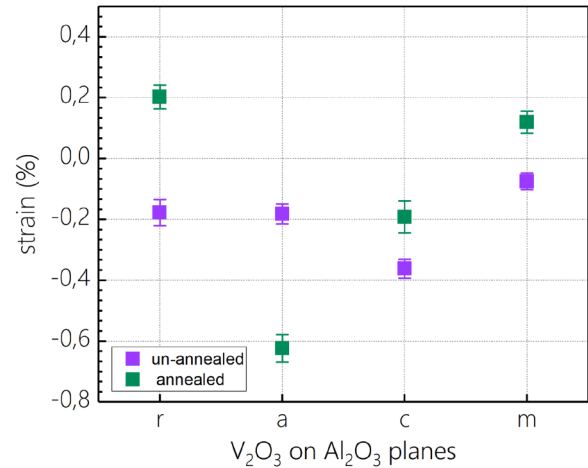


FIG. 3. Percentile out-of-plane strain calculated by extracting d -spacings determined from V_2O_5 peak positions in the XRD scans shown in Fig. 2.

primary peak aligns with the expected a -plane orientation, consistent with the substrate's crystallographic direction. Notably, a second peak corresponding to the c -plane orientation is also observed. This is significant, as the c -plane is a preferred orientation for V_2O_5 growth due to lower lattice mismatch with the Al_2O_3 substrate, suggesting the presence of mixed crystallographic orientations in the films. Considering the in-plane lattice constant of Al_2O_3 , which is lower than that of high temperature corundum V_2O_5 for all investigated surface orientations, the films can be thought of to be under compressive in-plane strain.¹⁷ A tensile out-of-plane strain should, therefore, be expected with a shift in the V_2O_5 peak position to lower angles compared to bulk values listed in the caption in Fig. 2 although compressive strain can also be observed for V_2O_5 grown on Al_2O_3 substrates.^{18,19}

An overview of the out-of-plane strain in the films relative to bulk values for V_2O_5 is given in Fig. 3. A positive strain is observed for the films grown on annealed r - and m -plane substrates while the other films show a negative value corresponding to compressive strain in the out-of-plane direction.

B. Temperature-dependent XRD

The crystal structure evolution of the heterostructure through the structural phase transition was investigated by performing x-ray diffraction measurements as a function of temperature upon heating. Figure 4 shows temperature-dependent XRD scans recorded from 100 to 300 K for the V_2O_5 films on annealed and un-annealed r -plane Al_2O_3 substrates. The results show distinct peaks at high and low temperatures, arising from the high-temperature rhombohedral phase and the low-temperature monoclinic phase.²⁰ As the temperature is reduced, a clear shift in the peak positions is observed corresponding to the transition of the film from the high temperature rhombohedral phase to the low-temperature monoclinic phase. The peak intensities and positions of the two phases were extracted by fitting the XRD data using

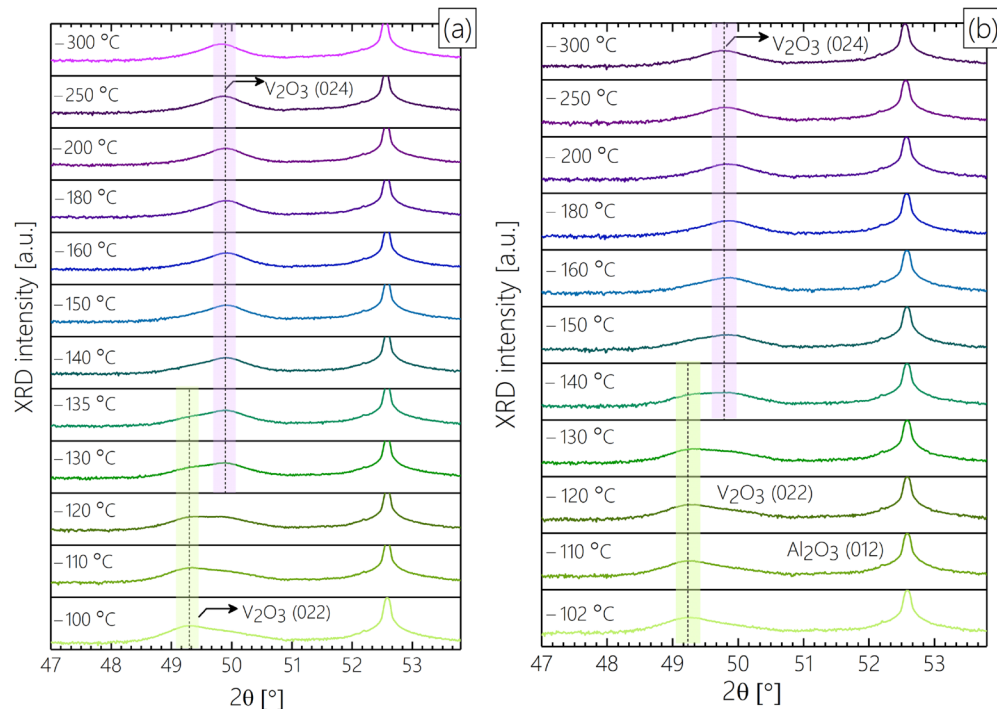


FIG. 4. Temperature-dependent x-ray diffraction scans recorded for the V_2O_3 film on r -plane Al_2O_3 (a) un-annealed and (b) annealed, as a function of temperature across the structural phase transition of V_2O_3 . The broken lines, along with shaded areas, represent the positions of the diffraction peaks for the rhombohedral and monoclinic phases of the V_2O_3 at high and low temperatures, respectively. The XRD peak positions are derived by fitting the peaks with a pseudo-Voigt function.

pseudo-Voigt function. The crystallographic phase fractions obtained from the peak fit at different temperatures followed by normalization with maximum value are shown in Fig. 5. The results indicate the middle of the transition temperature, where both monoclinic and rhombohedral V_2O_3 phase peaks are present at the same time, indicating phase coexistence region with comparable intensities at ≈ 134 and 117 K for films grown on annealed and unannealed r -plane Al_2O_3 , respectively.⁸ Therefore, controlling the annealing state of the substrate offers a potential method for tuning the phase coexistence region, which plays a critical role, as the most significant changes in the magnetic properties of the magnetic layer on top of V_2O_3 occur within this region.^{8,21–25} Interestingly, for the sample grown on the a -plane substrate, the c -component peak (006) across the SPT remains locked and exhibits only a small shift, whereas the a -component (110) shows a more noticeable peak shift, along with changes in intensity, indicating more intertwined directional structural changes [see Fig. S2(a) in the [supplementary material](#)].

C. Surface topography

The surface morphology of structures was investigated by atomic force microscopy. Representative AFM topographic images of V_2O_3 films on respective Al_2O_3 substrates are shown in Fig. 6. The surface roughness (RMS) values extracted from the images are

tabulated in Table I. These results can be related to a distinctive film growth environment of V_2O_3 on the differently oriented Al_2O_3 substrates.²⁶ For r , c , and a -plane, an increase in the lateral grain size was observed when deposited on to annealed substrates, along with the appearance of terraced surfaces. For m -plane, a dominant and highlighted appearance of terraced surfaces was observed with a higher roughness value, indicative of substantial changes in the surface morphology during the annealing of the substrate.

D. Electrical characterization

Figure 7 shows the resistance of the V_2O_3 films grown on annealed and un-annealed substrates with different surface orientations. In all cases, the films reveal clear metal-insulator transitions with different onset temperatures and magnitudes ranging from ≈ 1 to up to 6 orders of magnitude. Previous studies on V_2O_3 films grown on r -plane substrates^{14,27} have demonstrated that they exhibit a notably abrupt transition with increased MIT magnitude compared to films grown on the c -plane. Our results reveal that films grown on un-annealed r - Al_2O_3 substrates exhibited a MIT transition with substantially larger hysteresis and suppressed transition compared to film grown on un-annealed c -plane sapphire, along with transition temperature around 117 K [see Figs. 7(a) and 7(c)]. For the annealed substrates on the contrary, the c -plane films exhibit a suppressed transition with the transition temperature shifted to higher

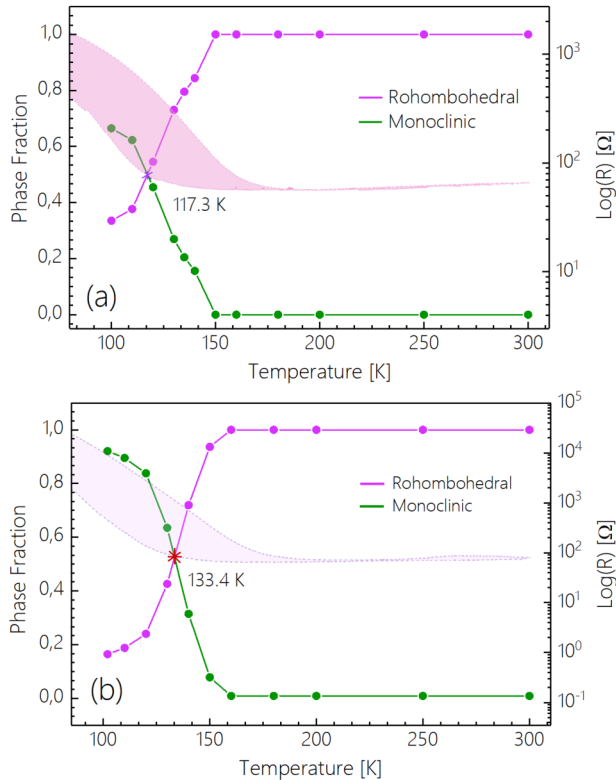


FIG. 5. Relative intensities of rhombohedral and monoclinic V_2O_3 Bragg peaks measured upon heating for the V_2O_3 film on (a) un-annealed and (b) annealed r -plane Al_2O_3 . The asterisk symbol marks the midpoint of the transition temperature, where both monoclinic and rhombohedral V_2O_3 phase peaks are present, indicating phase coexistence with comparable intensities.⁸ The shaded region shows the measured resistance vs temperature for the respective V_2O_3 films on un-annealed and annealed r -plane sapphire also shown in Fig. 7.

temperatures, compared to the film on annealed r -plane sapphire along with a shift in transition temperature to ≈ 134 K. The suppression in MIT magnitude for V_2O_3 film on c - Al_2O_3 compared to r - Al_2O_3 is due to the fact that the c axis is firmly clamped for V_2O_3 film deposited on to c - Al_2O_3 , whereas the V_2O_3 lattices on r -plane sapphire experience less hindrance in a axis expansion and c axis shrinkage due to substrate clamping, thereby resulting in less restriction on the transition characteristics. Consequently, a reduced spread in the c/a ratio of the films grown on r - Al_2O_3 is observed for varying O_2 flows, while a predominant effect on lattice modification is noted for varying growth temperatures in Ref. 14 and our previous work,²⁸ demonstrating the effect of substrate-induced strain, and the corresponding c/a ratio, on observed MIT characteristics. It is noteworthy to mention here that the transition temperature values were obtained by plotting $d(\ln R)/dT$ as a function of temperature⁹ and are in close agreement with those obtained by temperature-dependent XRD measurement. Table II summarizes the T_{MIT} values obtained for both heating and cooling cycles along with the measured hysteresis width for each system discussed in this work.

In the context of the magnitude of the MIT for V_2O_3 films deposited on annealed r -plane Al_2O_3 substrates, compared to unannealed substrates, the observed increase in MIT can be attributed to several interrelated factors, including reduced compressive strain and improved surface smoothness. X-ray diffraction (XRD) measurements indicate that annealing the r -plane Al_2O_3 substrate reduces the compressive strain in the V_2O_3 films by relaxing the lattice misalignment between the film and the substrate. This strain relief allows the V_2O_3 films to more freely undergo the necessary structural adjustments (such as c axis contraction and a axis expansion) during the MIT, leading to a more pronounced transition with higher magnitude.^{29,38}

Furthermore, AFM measurements show that the surface roughness of V_2O_3 films is significantly reduced when grown on annealed r -plane Al_2O_3 substrates, which suggests that the smoother, defect-free surface of the annealed substrate promotes more uniform film growth. The smoother surface reduces scattering centers in the film, which are known to broaden or suppress the MIT, leading to a sharper and higher-magnitude transition.³⁰ This reduction in roughness is consistent with findings in other studies, such as those by Sakai *et al.*,¹⁴ where they observed that the transport properties of V_2O_3 films are sensitive to surface roughness and strain. Specifically, smoother substrates result in more ordered thin films, enhancing the MIT characteristics due to the more uniform distribution of electronic and structural properties across the film.

In addition, substrate-induced strain plays a critical role in controlling the MIT of V_2O_3 films. For instance, the work by Brockman *et al.*³¹ on V_2O_3 films grown on c -plane sapphire substrates showed that substrate-induced disorder and strain can suppress the MIT, especially when the film experiences a strong c axis constraint. On the other hand, films grown on r -plane sapphire substrates have been found to exhibit less hindrance in lattice expansion due to the reduced misfit between the film and the substrate, which allows for a less restricted transition, as corroborated by the work of Sakai *et al.*,¹⁴ which demonstrated that films grown on r -plane sapphire exhibit more favorable strain conditions.

Furthermore, for V_2O_3 films grown on c -plane sapphire, the XRD analysis reveals a peak shift to lower angles for films on the annealed substrate (corresponding to a larger out of plane lattice parameter) and a reduction in the lateral grain size. Previous results have shown that the MIT magnitude is enhanced with larger grain size attributed to a smaller number of grain boundaries and defects.^{10,26,32} The shift in T_{MIT} to higher values corresponds to the lattice constant- c , which is reduced in out-of-plane direction implying compression in V-V atomic distances on the annealed substrates,^{33,34} modulating the orbital occupancy, which, in turn, triggers the MIT to be observed at a higher temperature. These results are in agreement with studies by Kalcheim *et al.*,³⁵ where it has been highlighted how strain, induced in a geometrically confined V_2O_3 thin film grown on a c -plane Al_2O_3 substrate, can alter the MIT characteristics.³⁶

Films deposited onto a -plane sapphire [see Fig. 7(b)] show a shift in T_{MIT} to a higher temperature for annealed substrates while maintaining the magnitude of the transition (within the temperature range investigated). This increase in T_{MIT} can be associated with un-relaxed strain for the film deposited on a -plane sapphire.¹

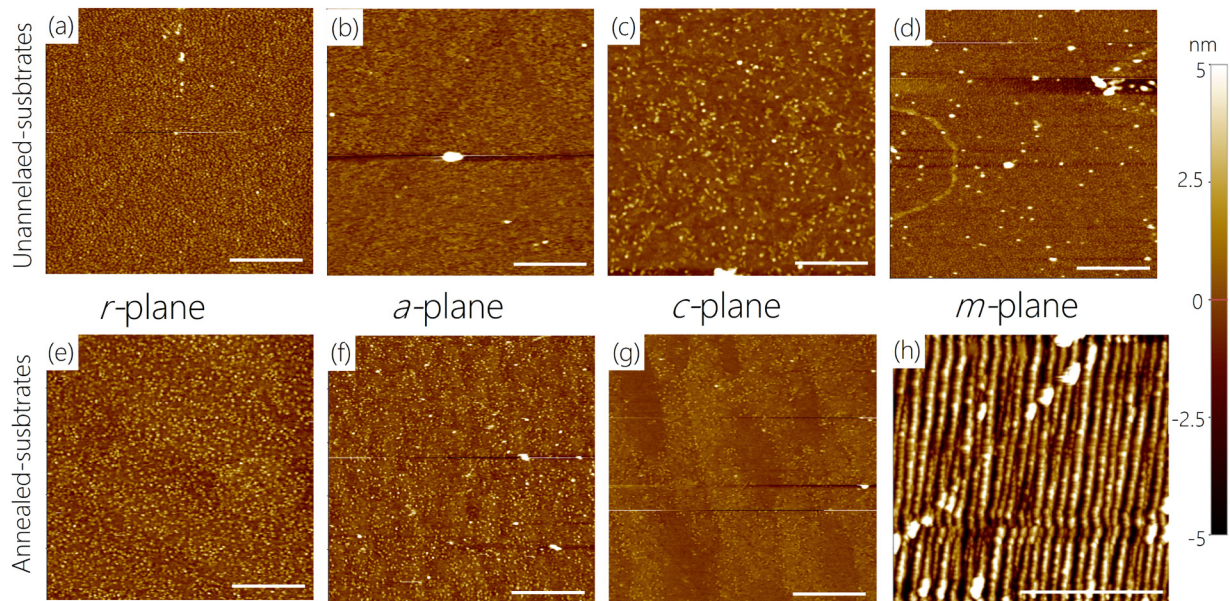


FIG. 6. $5 \times 5 \mu\text{m}^2$ AFM images of V_2O_3 films grown r , a , c , and m -plane Al_2O_3 on (a)–(d) un-annealed substrates and (e)–(h) annealed substrates. The scale bar provided is $1 \mu\text{m}$. The z-scale bar is provided on the right side for all scans.

This is further supported by the expansion of a axis as to balance the grain boundary free energy and the surface energy of the islands.³⁷ However, according to volume conservation, an out-of-plane compressive strain is induced to balance (as evident by a shift in the x-ray diffraction peak to higher values corresponding to in-plane tensile strain in the film). Thus, the compressive strain becomes enhanced in films deposited on annealed substrates for a -plane, thereby stabilizing the transition.^{1,14} Such behavior has been noted in other studies where the substrate's role in epitaxial growth alters the lattice dynamics of vanadium oxide, particularly in anisotropic orientations like a -plane.^{1,38} Furthermore, the room temperature resistance obtained for c -plane is lower than that of a -plane in line with the results by Allimi *et al.*¹

In addition, annealing improves the crystalline quality of the substrate, which strengthens the film–substrate interface while promoting larger grains and reducing defect density. This leads to enhanced “clamping,” which restricts out-of-plane relaxation during lattice adjustments, thereby amplifying compressive strain

in the vertical direction. This phenomenon stabilizes structural phases, contributing to the observed increase in T_{MIT} .^{1,12,39}

The a -plane orientation further creates a unique strain environment due to its lower symmetry compared to r - and c -plane substrates.^{40,41} Strain in these systems directly impacts the orbital occupancy of vanadium atoms, with out-of-plane compressive strain favoring configurations that stabilize the insulating phase. Consequently, this results in the upward shift in T_{MIT} without significant changes in the transition magnitude.^{31,39}

The V_2O_3 films deposited on un-annealed m -plane sapphire showed a suppressed magnitude of the transition with T_{MIT} shifted to lower temperatures [see Fig. 7(d)]. This reduction in the MIT

TABLE II. Characteristics of V_2O_3 films deposited onto various planes of Al_2O_3 , both in un-annealed (NA) and annealed (AN) states, extracted from MIT characteristic plots in Fig. 7 and XRD plots in Fig. 2.

Substrate orientation	$T_{\text{MIT-cooling}}$ T (K)	$T_{\text{MIT-heating}}$ T (K)	Hysteresis	
			width T (K)	2θ (°)
$r\text{-Al}_2\text{O}_3$ (NA)	117	154	37	24.35
$a\text{-Al}_2\text{O}_3$ (NA)	131	165	34	36.29
$c\text{-Al}_2\text{O}_3$ (NA)	140	161	21	38.64
$m\text{-Al}_2\text{O}_3$ (NA)	98	128	30	65.22
$r\text{-Al}_2\text{O}_3$ (AN)	134	177	43	24.22
$a\text{-Al}_2\text{O}_3$ (AN)	145	174	29	36.46
$c\text{-Al}_2\text{O}_3$ (AN)	150	179	29	38.59
$m\text{-Al}_2\text{O}_3$ (AN)	136	164	28	65.09

TABLE I. RMS roughness values of V_2O_3 films deposited onto various planes of Al_2O_3 , both in un-annealed and annealed states.

Substrate orientation	RMS (nm)	
	Un-annealed	Annealed
$r\text{-Al}_2\text{O}_3$	0.953	0.806
$a\text{-Al}_2\text{O}_3$	0.578	0.945
$c\text{-Al}_2\text{O}_3$	0.574	0.424
$m\text{-Al}_2\text{O}_3$	0.835	3.653

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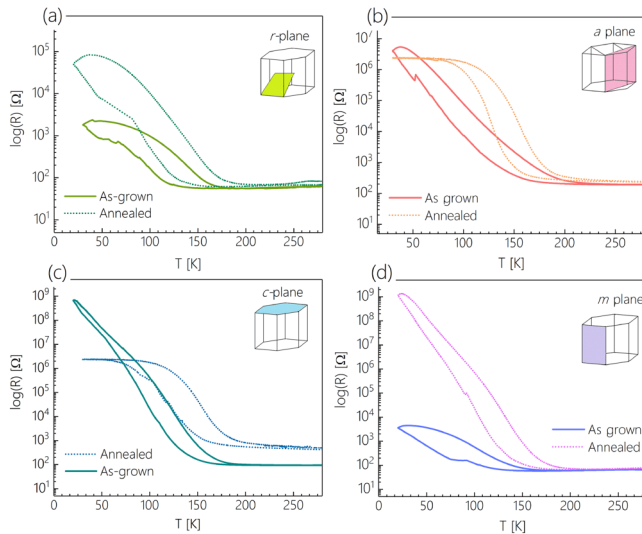


FIG. 7. (a)–(d) Comparison of resistance as a function of temperature for V_2O_3 films deposited on r , a , c , and m -plane Al_2O_3 for both annealed and un-annealed substrates.

characteristics can be attributed to increased out-of-plane compressive strain and a lack of epitaxial growth of the film, as revealed by XRD scans. As with other sapphire substrates, annealing the substrates tends to form terraced surfaces leading to an increased epitaxy of the V_2O_3 film and reduced out-of-plane compressive strain. The film grown on the annealed m -plane substrate shows, therefore, a substantial increase in MIT magnitude (≈ 6 order of magnitude) and a shift in T_{MIT} to higher temperature, close to that of bulk V_2O_3 .

The observed high resistance in the insulating region is a direct consequence of the improved structural integrity, which facilitates a clearer distinction between the two phases.^{20,39} The pronounced resistance change on the annealed m -plane substrate is unique due to the anisotropic strain introduced by the m -plane orientation, which has lower symmetry compared to other substrate orientations.^{40,42} This anisotropy likely promotes the stabilization of the insulating phase while reducing the presence of mixed phases during the transition. Studies have shown that the strain conditions of m -plane substrates can lead to distinct resistance behaviors, particularly enhancing the sharpness and magnitude of the MIT when film quality is optimized.^{43,44} Additionally, the increased roughness at the buried interface, particularly in the annealed m -plane substrate, likely acts as a structural perturbation during cooling, affecting the nucleation and growth dynamics of the insulating and metallic domains. This mechanism aligns with percolation models for the MIT in V_2O_3 and VO_2 , where interface roughness influences the percolation pathways and domain connectivity.⁴⁵ Consequently, the enhanced roughness in the insulating regime possibly leads to a larger resistance change compared to the metallic state.

As previous studies have shown, the structural phase transition (SPT) and MIT are coupled even for films with varying degrees of

strain and T_{MIT} .^{20,36} This coupling is demonstrated in Fig. 5 for V_2O_3 films on both annealed and un-annealed r - and annealed a -plane sapphire [see Fig. S2(b) in the [supplementary material](#)], where the crossover from the rhombohedral to the low-temperature monoclinic phase intercepts approximately at the T_{MIT} from metallic to insulating phase for films when cooled down to low temperatures. The T_{MIT} values extracted for V_2O_3 on un-annealed and annealed r -plane Al_2O_3 are ≈ 117.3 and 133.4 K.

The interplay between the structural and electronic transitions in V_2O_3 , particularly the relationship between its SPT and MIT, provides critical insight into its transport properties. The phase coexistence region, where both the rhombohedral metallic and monoclinic insulating phases coexist, corresponds to the temperature range where resistance changes most rapidly. Temperature-dependent XRD measurements reveal that annealed substrates reduce strain, leading to a narrower coexistence region and enabling a sharper and steeper resistance transition. In contrast, unannealed substrates introduce higher defect densities and strain, broadening the coexistence region and resulting in a more gradual change in resistance.^{39,44,46} Further, studies using complementary techniques, such as infrared spectroscopy, confirm a robust coupling between the structural and electronic transitions, regardless of substrate orientation or strain state.⁴⁶ This coupling underscores that the SPT directly influences the MIT, with the structural changes governing the abruptness and temperature range of the transition.^{20,39} The improved crystallinity and reduced strain in films grown on annealed substrates facilitate clearer structural adjustments, aligning with more pronounced MIT behavior.³¹

IV. CONCLUSIONS

The T_{MIT} of V_2O_3 epitaxial films deposited onto different sapphire substrate orientations, extracted using $\frac{d \ln(R)}{dT}$ function (not shown here) from Fig. 7, reveals intriguing behavior. The T_{MIT} values of the films consistently fall below the bulk transition temperature ≈ 150 K¹⁴ for the films grown on un-annealed substrates. The observed order of transition temperatures follows a sequence of $T_{\text{MIT}}^m < T_{\text{MIT}}^r < T_{\text{MIT}}^a < T_{\text{MIT}}^c$, aligning closely with the findings of previous studies.^{1,20} This agreement underscores the robustness of the observed trends across different investigations. For the films deposited onto annealed substrates, the transition temperature order shifts as $T_{\text{MIT}}^r < T_{\text{MIT}}^m < T_{\text{MIT}}^a < T_{\text{MIT}}^c$, suggesting a clear influence of substrate annealing on the T_{MIT} behavior. These results underscore the pivotal role of the substrate in determining the T_{MIT} dynamics, highlighting the intricate interplay between film–substrate interactions, strain character, and surface morphology.

SUPPLEMENTARY MATERIAL

See the [supplementary material](#) for temperature-dependent x-ray diffraction scan recorded for the V_2O_3 film on un-annealed a -plane Al_2O_3 .

ACKNOWLEDGMENTS

This work was supported by funding from the Icelandic Research Fund (Grant Nos. 207111 and 228957) and Landsvirkjun

Energy Fund (Grant No. NÝR-29-2024). Instrumentation funding from the Icelandic Infrastructure Fund is acknowledged.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Muhammad Taha Sultan: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Funding acquisition (equal); Investigation (equal); Methodology (equal); Software (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Kristina Ignatova:** Conceptualization (lead); Formal analysis (supporting); Investigation (equal); Methodology (equal); Software (supporting); Validation (equal); Writing – original draft (supporting); Writing – review & editing (equal). **Snorri T. Ingvarsson:** Funding acquisition (supporting); Resources (supporting); Validation (equal); Writing – review & editing (equal). **Unnar. B. Arnalds:** Conceptualization (equal); Funding acquisition (equal); Project administration (equal); Resources (equal); Supervision (equal); Validation (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available within the article and its [supplementary material](#).

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