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Synthesis and Characterization of V_2O_5 Nanorods on Different Substrates under Thermal Annealing

Arya Preshit Rajeshirke[a*],Sana jay Biswas[b]

[a]*Garodia International Centre for Learning Mumbai, India*-400077
[b]*Pion Academy Mumbai, Maharashtra, India-400018*
[a]*Email:aryarajeshirke57@gmail.com*

Abstract

Vanadium pentoxide (V_2O_5) nanorods have arisen as interesting functional materials owing to their distinctive one-dimensional structure, adjustable bandgap, and exceptional electrochemical and optical characteristics. Their synthesis and characterization under diverse thermal annealing conditions on various substrates have garnered considerable interest for applications in photodiodes, gas sensors, and electrochromic devices. Various synthetic methods, such as hydrothermal growth, spray pyrolysis, and chemical pyrophoric reactions, have facilitated the precise synthesis of V_2O_5 nanorods exhibiting substrate-dependent structural, morphological, and electrical characteristics. Thermal annealing is essential for adjusting crystallinity, defect density, optical absorbance, and electrical conductivity. Recent research indicate that substrate type, annealing duration, and temperature substantially impact nanorod orientation, growth density, and interfacial characteristics, thereby affecting device performance. This paper synthesizes advancements in synthesis processes, annealing effects, and substrate influence on V_2O_5 nanorods, establishing a basis for customizing nanostructures for energy, sensing, and optoelectronic applications.

Keywords: Synthesis; nanorods; annealing.

1.Introduction

Vanadium pentoxide (V_2O_5) has gained great scientific interest due to its layered orthorhombic crystal structure, broad band gap (~2.2-2.4 eV), and complex redox chemistry, making it highly flexible across energy storage, sensing, catalysis, and optoelectronic applications. In lithium-ion batteries, its layered structure allows for quick Li^+ intercalation. In gas sensors and photocatalysts, its surface chemistry and oxygen vacancies improve reactivity and selectivity [1, 2]. Nanorods are unique in their anisotropic development, high aspect ratio, and improved surface-to-volume ratio compared to other V_2O_5 morphologies.

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* *Corresponding author.*

These features promote superior charge transport and light absorption compared to isotropic nanoparticles, making them highly desirable in electrochromic devices, photodetectors, and gas sensors[3, 4].

Nanorod arrays also provide increased mechanical stability and directional channels for ion/electron diffusion, which are crucial for enhancing cycling stability in energy storage devices.

The substrate significantly affects the nucleation, growth orientation, and morphology of V_2O_5 nanorods. For example, nanorods grown on conductive substrates such as fluorine-doped tin oxide (FTO) or indium tin oxide (ITO) frequently exhibit increased crystallinity and vertical alignment, which improves electrochemical performance. In contrast, insulating substrates such as glass or sapphire influence surface energy and defect development, resulting in differences in rod density and aspect ratio [5, 6]. Equally important is the effect of thermal annealing in controlling crystallinity, phase purity, oxygen vacancy concentration, and defect states. Post-growth annealing at 300-500 °C can turn amorphous or weakly crystalline V_2O_5 into well-defined orthorhombic nanorods, improving conductivity and optical absorbance [6]. Annealing not only improves crystallinity but also changes the electrical structure by adjusting oxygen stoichiometry, which is critical for applications like electrochromism and sensing.

One-dimensional (1D) vanadium pentoxide (V_2O_5) nanorods have benefits over bulk and isotropic nanostructures, including anisotropic crystal formation and a high surface-to-volume ratio. The layered structure of V_2O_5, with weak van der Waals interactions between pyramidal layers, promotes anisotropic bonding and directional crystal growth, resulting in elongated nanorod morphologies [7]. This anisotropy leads to increased electrical conductivity along the rod axis and directional ion diffusion paths, both of which are necessary for energy storage and optoelectronicapplications.Nanorods have a substantially greater surface-to-volume ratio than bulk films or bigger particles, allowing for more active surface redox reactions and boosting catalytic and sensing efficiency. Nanorod arrays, for example, have been found to prevent irreversible phase transitions during lithium intercalation due to their vast surface area and short diffusion lengths [8]. In addition to electrochemical benefits, anisotropic geometry improves optical and electronic properties. V_2O_5 nanorods have higher light absorption and photoconductivity than granular films, making them ideal for photodiodes and electrochromic devices [9]. Directional charge transport reduces recombination losses, and aligned nanorod arrays have higher electron mobility than disordered nanoparticles [10]. Furthermore, the mechanical robustness of nanorod designs ensures longer cycling life in lithium-ion batteries and electrochromic devices. Coralline and vertically oriented nanorod arrays have shown better structural stability and excellent reversibility in electrochemical cycling [11]. V_2O_5 nanorods are a versatile material for energy storage, sensors, and optoelectronic devices due to their anisotropic charge transfer, improved surface reactivity, and structural stability.

2. Fundamentals of V_2O_5 Nanostructures

Vanadium pentoxide (V_2O_5) nanostructures have arisen as multifaceted materials owing to their distinctive layered crystal architecture, polymorphism, and adjustable electrical characteristics. The orthorhombic α-V_2O_5 phase consists of [VO_5] square pyramids interconnected into layers through shared oxygen atoms, with van der

Waals gaps that facilitate ion intercalation, rendering it significant for electrochemical applications [12]. Vanadium's capacity to assume several oxidation states ($V^{5+}/V^{4+}/V^{3+}$) underlies its extensive redox activity, which is crucial for applications in energy storage, catalysis, and sensing [13].

The development of V_2O_5 nanostructures often adheres to diffusion-limited or anisotropic crystallization mechanisms, influenced by the structural anisotropy of the layered lattice. Techniques include hydrothermal synthesis, sol–gel processing, spray pyrolysis, and vapor-phase methods have been extensively employed to customize one-dimensional (nanorods, nanowires), two-dimensional (nanosheets), and hierarchical morphologies [7]. The morphology of V_2O_5 nanostructures significantly influences their electrochemical performance, as high-aspect-ratio nanorods or nanosheets offer reduced diffusion pathways for ions and increased surface areas for redox activity, resulting in improved charge storage and catalytic efficiency [14]. The essential importance of V_2O_5 nanostructures resides in their structure–property relationships; the interaction of layered crystal chemistry, morphology, and redox activity facilitates multifunctionality in batteries, supercapacitors, electrochromic devices, and photocatalysis [2, 15].

2.1 Crystal structure and polymorphs of V_2O_5

The most stable and extensively researched vanadium oxide is vanadium pentoxide (V_2O_5), which crystallizes in a layered orthorhombic form in ambient circumstances. The [VO_5] square pyramids that make up the orthorhombic α-V_2O_5 (space group Pmmn) share corners and edges, creating double chains that are connected by oxygen atoms to form a multilayer configuration. Van der Waals interactions provide a weak link between these layers, facilitating ion intercalation and supporting their application in sensors, batteries, and catalysis[12].V_2O_5 displays a number of polymorphs with varying structural connectivity and stability in addition to the orthorhombic α-phase. Among the reported polymorphs are: A metastable variation of the orthorhombic phase with minor distortions is α′-V_2O_5.β-V_2O: a monoclinic structure with rearranged [VO_5] pyramids that forms at high temperatures. γ-V_2O: an intermediate phase that manifests under specific electrochemical or annealing conditions. δ- and ε-V_2O_5: three-dimensional framework high-pressure polymorphs. The flexible vanadium-oxygen system, which may generate more than 50 stable and metastable phases based on synthesis temperature, pressure, and oxygen partial pressure, is the cause of these polymorphs[16]. With distinctive vibrational modes connected to V–O stretching and bending, Raman and X-ray diffraction experiments have proven very useful in differentiating these polymorphs [17, 18]. The functional flexibility of V_2O_5 is intimately related to its polymorphism. For instance, it has been demonstrated that metastable β- and γ-polymorphs have better ion transport and electronic conductivity than the α-phase, which makes them promising for enhanced metal-ion batteries[19]. Furthermore, the tunability of V_2O_5 for particular applications is highlighted by its reversible transformation between polymorphs via heat or electrochemical treatment.A rich polymorphism resulting from flexible [VO_5] pyramid connections defines the crystal chemistry of V_2O_5. Optimizing V_2O_5 nanorods for energy storage, electrochromism, and catalytic applications requires an understanding of the ability to manage these structural changes. Figure 1 shows the Raman spectra of various polymorphs of vanadium pentoxide (V_2O_5), specifically the α-, β-, γ-, and ε'-phases, together with their respective crystal structures. Each polymorph is characterized by distinct Raman peaks, indicating differences in V–O bonding conditions and lattice vibrations associated with the unique crystal symmetry. The diagram highlights the relationship between structural variations and vibrational modes, offering insights for phase identification and material characterization in energy storage, sensing, and catalytic applications [18].

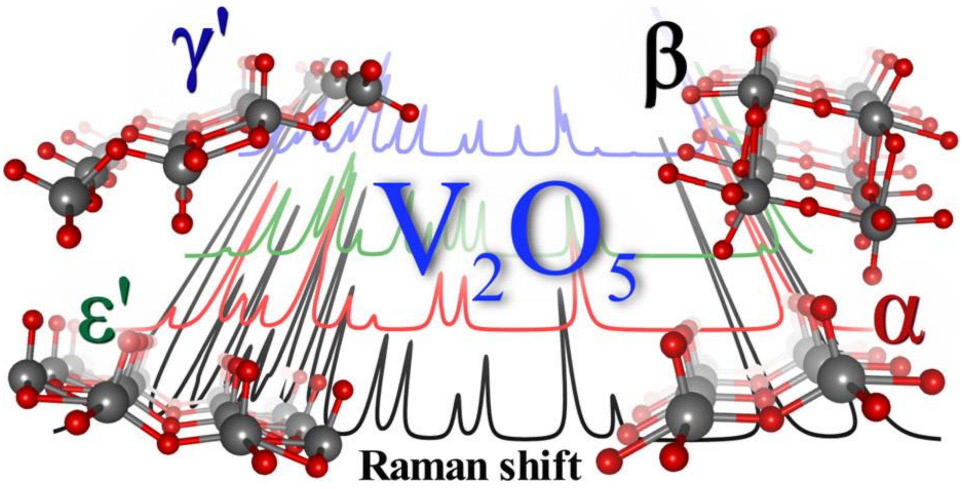

Figure 1: Crystal structures of α-, β-, γ- and ε'-V_2O_5 polymorphs [18]

Vanadium pentoxide (V_2O_5) is known to appear in different forms, or polymorphs, whose stability is affected by temperature, pressure, and the conditions of synthesis. At room temperature, orthorhombic α-V_2O_5(space group Pmmn), which is made up of layers of [VO_5] square pyramids, is the most stable phase. When we measure X-ray diffraction (XRD), we usually see sharp peaks at $2\theta \approx 15.4°$, 20.3°, and 26.2°. These are the (200), (001), and (101) planes, respectively [20]. More proof of this structure comes from Raman spectroscopy, which shows strong bands near 995 cm^{-3} (V=O stretching) and 700 cm^{-3} (V–O–V bending).The α-phase changes into β-V_2O_5, a monoclinic polymorph, when the pressure is high (about 7 GPa). This was shown by tests that combined Raman spectroscopy and neutron diffraction. Its vibrational features are unique around 860 cm^{-3}, and its lattice improvements show two formula units per unit cell [21].Recently, Luo and his colleagues (2022) used high-resolution transmission electron microscopy (HRTEM) to directly see the lattice fringes of α- and α-V_2O_5. They showed that lithiation processes in nanostructured polymorphs are controlled by cation reordering rather than structural collapse [22]. Raman and XRD studies have also found metastable polymorphs like γ′-V_2O_5, which have extra bands at ~960 cm^{-3} and 450 cm^{-3} that are different from the α-phase [23].

2.2 Role of substrates in determining morphology and properties

The selection of substrate is a pivotal element affecting the nucleation, growth orientation, and overall characteristics of V_2O_5 nanorods. The properties of the substrate, including lattice mismatch, surface energy,roughness, and conductivity, directly influence the shape and crystallinity of theresultingnanostructures.Hydrothermal synthesis research indicates that the substrate type influences nanorod alignment and density, with glass, silicon, and metallic substrates yielding markedly diverse morphologies due to differences in surface energy and chemical reactivity [24]. When utilizing conductive substrates like ITO and FTO, V_2O_5 nanorods often exhibit enhanced uniformity and vertical alignment, hence optimizing electron transport channels and rendering them more appropriate for electrochromic and energy storage applications

Reference [25]. Likewise, the p-Si substrate facilitates the creation of V_2O_5/p-Si heterojunctions with improved optoelectronic characteristics, wherein substrate-induced stress and interface effects affect charge transport and optical absorption [26]. Stainless steel (SS) and various flexible substrates have been examined, revealing porous nanostructures conducive to electrochemical activity, emphasizing the influence of substrate porosity and roughness on nanorod development patterns [27].

Recent research on 3D ordered macroporous (3DOM) templates has shown the transformation from porous films to nanorod arrays through substrate-guided nucleation, resulting in improved optical modulation and electrochemical stability in electrochromic devices [28]. These findings underscore that the substrate not only affects the physical dimensions of nanorods but also alters their electrical, optical, and electrochemical capabilities.Substrates function as active determinants of nanorod shape, orientation, and functional behavior, rather than only serving as passive supports. The meticulous selection of substrates designed for particular applicationssuch as conductive oxides for energy storage, semiconductors for optoelectronics, or porous metals for catalysiscontinues to be a crucial technique in enhancing the performance of V_2O_5 nanorods.Several experiments have shown that the type of material has a big effect on the shape, crystallinity, and electrical properties of V_2O_5 nanorods.Takahashi and his colleagues made single-crystalline V_2O_5 nanorod arrays on indium tin oxide (ITO) substrates using template-assisted electrodeposition. They said that the conductive substrate made it possible for the nanorods to be lined up vertically and improved charge transport. The electrochemical tests showed that the nanorods had a higher specific capacitance and more steady Li^+ intercalation than nanorods grown on non-conducting substrates [25].

Three-dimensional substrates that help with templates make controlled nanorod building even easier. When grown on porous ITO templates, Liu and his colleagues showed how 3D ordered macroporous (3DOM) V_2O_5 films can change into nanorod structures. The nanorods that were made had better optical modulation ($\Delta T >$ 40% at 633 nm) and great cycle stability when used in electrochromic devices. This showed that the properties of a material are related to its shape [28]. Electrochromic efficiency has also been seen to be affected by substrate-induced crystallization. Tong and his colleagues found that V_2O_5 nanorods grown on conductive ITO showed better coloration efficiency (55 $cm^2\ C^{-3}$) and faster reaction times than those grown on insulating glass. This showed a direct link between the substrate's conductivity and electrochromic dynamics [11].

Overall, these studies show that substrates are not just passive supports; they play an active role in controlling the growth, alignment, crystallinity, and electrical and optical features of nanorods. Conductive substrates like ITO and FTO support nanorods that are aligned vertically and have better electron transport, while rough or porous substrates improve surface reaction. This shows how important substrate engineering is for customizing V_2O_5 nanostructures for specific uses.

2.3 Influence of Thermal Annealing on Crystallinity, Phase, and Defect States

In order to adjust the crystallinity, phase composition, and defect density of V_2O_5 nanorods, thermal annealing is essential. As-synthesized nanorods often exhibit partially amorphous or poorly ordered structures, which require thermal treatment to achieve phase-pure orthorhombic V_2O_5. Annealing generates phase transformations, as several studies have shown. With better crystallinity and sharper diffraction peaks, V_2O_5 nanorods annealed between 300 and 600 °C, for instance, transition from an anorthic phase to the thermodynamically stable orthorhombic phase[26].Similarly, well-defined 1D morphologies are stabilized and structural disorder is suppressed when chemically produced nanorods undergo controlled annealing [29]. Additionally, annealing affects defect states and oxygen stoichiometry, both of which are essential for V_2O_5functional characteristics. By reducing oxygen vacancies, which are frequently created in asgrown nanorods, annealing can enhance charge transport and optical transparency. On the other hand, annealing may redistribute defects in some circumstances, resulting in defect-assisted luminescence or improved nonlinear optical performance [30, 31]. Defect-mediated radiative recombination, for example, has been demonstrated to produce strong visible light at room temperature from annealed nanorods.

Equally important is the annealing time. In general, longer annealing times promote grain development and crystallinity, but they can also lower surface area and coarsen nanostructures, which could impair electrochemical performance. Long-term annealing of spray-pyrolyzed V_2O_5 nanorods boosted crystallinity but changed defect-related photoluminescence [6].

3. Synthesis Strategies for V_2O_5 Nanorods

3.1 Solution-based methods (sol-gel, hydrothermal, precipitation)

Solution-based synthesis methods have been widely utilized for the fabrication of V_2O_5 nanorods owing to their simplicity, scalability, and capacity to modify morphology via reaction parameters. The sol–gel process is notably versatile, encompassing the hydrolysis and condensation of vanadium alkoxides or salts to produce a gel, succeeded by regulated drying and annealing. This method facilitates exact regulation of stoichiometry and porosity, yielding nanostructures with customized surface areas for use in catalysis and energy storage [32]. Non-hydrolytic sol–gel alternatives have been created to address stability concerns and produce high-purity nanocrystals at comparatively low temperatures [33].

The hydrothermal method is a prevalent technique that utilizes high temperature and pressure in enclosed autoclaves to facilitate the anisotropic growth of nanorods. Modifying parameters such as precursor concentration, pH, and reaction duration during hydrothermal synthesis produces high-aspect-ratio V_2O_5 nanorods and nanosheets with improved crystallinity. Mu and his colleagues produced V_2O_5 nanorods using hydrothermal treatment and shown that dimensionality significantly affected their electrochemical characteristics [34]. Recently, surfactants like Pluronic P123 have been used into hydrothermal systems to reduce agglomeration and enhance morphological homogeneity [35].

The precipitation process provides a more straightforward and cost-effective alternative, generally involving the interaction of vanadium salts with precipitants (such as ammonia or oxalates) to generate intermediate hydroxides or oxides that can be annealed into V_2O_5 nanorods. Although less accurate than sol–gel or hydrothermal methods, precipitation is efficient for generating substantial amounts of nanorods and has been effectively employed for transition-metal oxides such as V_2O_5 [36]. Recent advancements encompass the integration of precipitation with template-assisted growth to enhance the alignment and homogeneity of nanorods [37]. Sol–gel techniques enable precise compositional regulation, hydrothermal synthesis produces extremely crystalline and anisotropic nanostructures, and precipitation presents ease and scalability. The selection of these solution-based approaches is contingent upon the specific application, such as high-performance electrochemical devices, large-scale catalysis, or optical nanostructures.

3.2 Physical vapor methods (CVD, PVD, sputtering)

The ability of physical vapor deposition (PVD) techniques to produce high-purity, crystalline nanostructures with controlled thickness and orientation has led to their widespread use in the synthesis of V_2O_5 nanorods and thin films. These techniques include chemical vapor deposition (CVD), magnetron sputtering, and related plasma-assisted methods.

Chemical Vapor Deposition (CVD): This process allows vanadium oxides to be directly deposited from volatile precursors in a controlled environment, which promotes the formation of superior, crystalline nanorods on a variety of substrates. Tungsten-doped V_2O_5 nanorod films formed using hot-filament CVD in conjunction with sputtering have been shown in recent work to exhibit improved gas-sensing characteristics as a result of the synergistic effects of doping and nanoscale morphology [38]. Figure 2: Schematic representation of V_2O_5 thin film deposition methods V_2O_5 atoms are vaporized from a heated crucible and condense on the substrate in a vacuum chamber in (a) physical vapor deposition (PVD); and (b) chemical vapor deposition (CVD), in which precursor molecules break down on a heated substrate surface, producing V_2O_5 films while byproducts are extracted using a vacuum system [39]. These techniques are frequently used to regulate the V_2O_5 nanostructures' crystallinity, shape, and film thickness.

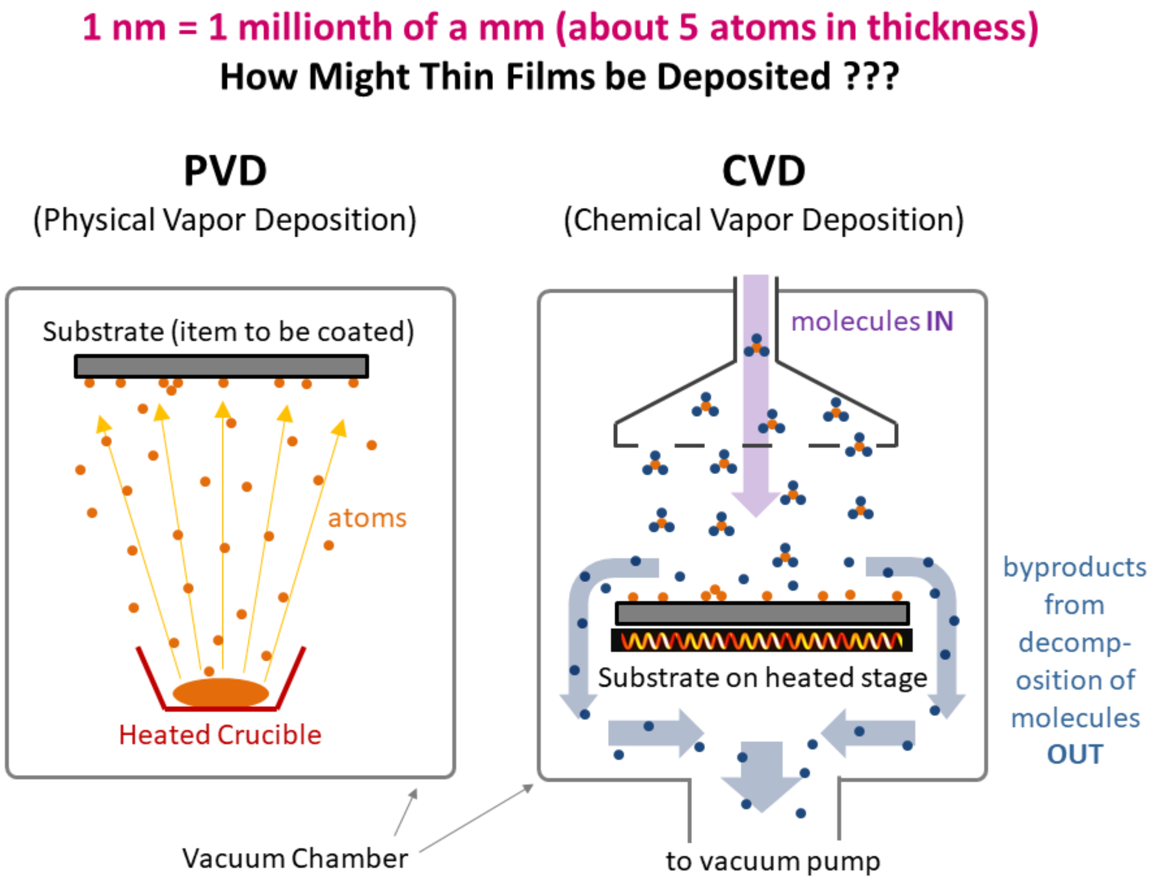

Figure 2: Deposition of V_2O_5 thin films using Physical Vapor Deposition (PVD) and Chemical Vapor Deposition (CVD) techniques [39]

Rare nanostructures like V_2O_5 nanoplates and nanoflakes with noticeable anisotropy and high surface activity have also been produced using plasma-assisted CVD methods [40]. Sputtering: Because of its homogeneity and scalability, RF magnetron sputtering is still the most widely used technique for creating VO_5 films and nanorods. Research has demonstrated that sputtering parameters including power, gas ratio, and substrate type have a major impact on morphology, defect density, and phase purity. For instance, Liu and his colleagues reported V_2O_5/metal/V_2O_5 multilayers made by RF sputtering, which allowed for regulated reduction paths to produce stable, thermally sensitive VO_2 films [41].Similarly, Al Otaibi illustrated the value of sputtering in thermochromic and optoelectronic device applications by demonstrating RF magnetron sputtering as a scalable method for creating vanadium oxide coatings across large surfaces [42]. General PVD Techniques: PVD includes evaporation and plasma-assisted sublimation in addition to sputtering. For optoelectronic and electrochromic applications, these techniques offer excellent control over nanostructure density, crystallinity, and alignment. Due to its adaptability and reproducibility for nanostructured morphologies, PVD has been the most popular method for V_2O_5 thin films since the late 20th century, according to Beke's thorough assessment [43]. V_2O_5 nanorods with adjustable crystallinity, orientation, and composition may be synthesized reliably and controllably using CVD, sputtering, and PVD techniques. Physical vapor pathways are essential for customizing V_2O_5 nanostructures for cutting-edge functional devices, even if sputtering is the predominant method for scalable thin-film development. CVD and plasma-assisted procedures provide access to distinct nanorod morphologies and doping schemes.

3.3 Electrochemical and template-assisted synthesis

Electrochemical synthesis is a simple and easy-to-control way to make V_2O_5nanorods. It usually involves depositing vanadium precursors on conductive surfaces during an anodic process. This method lets you fine-tune the shape by changing the applied potential, the electrolyte makeup, and the deposition time [2].For example, showed how to make uniform V_2O_5 nanorods (about 100–200 nm diameter) using a polystyrene-sphere template-assisted electrodeposition method. This led to ordered arrays with more surface area and better lithium-ion storage performance than bulk films. In the same way, V_2O_5 nanorods that were formed electrochemically have a high specific capacitance and stable charge–discharge cycling. This is because their shape is not uniform and they are closely connected to the conductivesubstrate [44].Template-assisted synthesis is another strong way to make nanorods that are highly ordered and have precise dimensions. Nanorod alignment is helped by hard templates like anodic alumina membranes or polystyrene beads. On the other hand, hierarchical and porous shapes can be made with soft templates like surfactants and block copolymers [45]. Wu and his colleagues reported making rattle-type V_2O_5 hollow microspheres using template-assisted synthesis. These microspheres had a reversible lithium storage capacity of about 420 mAh g^{-3} and were more stable during cycling than their non-templated peers [46]. Recently, Kim and Lee made hierarchical V_2O_5 hollow microspheres using template-assisted solvothermal methods. They reported high specific capacitance and good reversibility, showing that template shape strongly affects the performance of nanostructures [47]. Some researchers, Thakur and his colleagues, used a NaCl template-assisted method to make V_2O_5@rGO nanorods that worked better as cathode materials in lithium-ion batteries[48].Overall, electrochemical deposition can be scaled up and directly deposited on electrodes, while template-assisted methods allow precise control over the shape and structure of the layers. Both methods make V_2O_5 nanorods with better electrochemical qualities. This makes them very interesting for using in energy storage, catalysis, and electrochromic.

A comparative overview of the different synthesis techniques used to create V_2O_5 nanorods, such as solution-based, electrochemical, and template-assisted approaches, is shown in Table 1. The main precursors, reaction parameters, and final nanorod properties acquired under various experimental settings are described. For example, the hydrothermal approach creates monoclinic V_2O_5 nanorods that are approximately 0.55 µm long by heating ammonium metavanadate or V_2O_5 powder with surfactants and acids to temperatures between 160 and 200 °C. By using sodium hydroxide or vanadyl sulfate as precursors, the sol-gel or precipitation method produces orthorhombic V_2O_5 nanoparticles or nanorods with sizes that can be adjusted based on calcination and aging conditions. The creation of highly ordered, single-crystalline nanorod arrays with diameters ranging from 100 to 200 nm and lengths up to 10 µm is made easier by electrochemical and template-assisted techniques, which show exact control over morphology through annealing conditions and voltage.

Table1: Comparative of V_2O_5 nanorod production methods, critical parameters, and final morphologies

Synthesis Strategy	Method Specifics	Precursor(s)	Key Parameters	Experimental Data (Nanorod Dimensions)	Ref. Example
Solution-Based Methods	Hydrothermal	Ammonium metavanadate (NH4VO3) or V2O5 powder NH4VO3 Additives: Surfactants (e.g., CTAB), Acids (H2SO4, HNO3), Solvents (H2O, Ethanol)	Temperature: ≈160−200∘C Time: ≈24−72 h Concentration: 0.06−0.1 M NH4VO3	Lengths: ≈0.55 µm (post-annealing) Monoclinic V2O5 phase	[49]
	Sol-Gel/Precipitation	V2O5 in H2O2 followed by precipitation/aging Vanadyl sulfate hydrate (VOSO4·nH2O), Sodium hydroxide (NaOH) (Surfactant-mediated)	Aging Temp: ≈60−90∘C Post-calcination Temp: ≈400−600∘C	Nanoparticles (45-160 nm) or nanorods (30-90 nm diameter, 260-600 nm length) achieved by varying precursors/surfactant High purity Orthorhombic V2O5 upon calcination	[50]
Electrochemical & Template-Assisted	Electrochemical Deposition (Template-Assisted)	V2O5 dissolved in H2O2, then H2SO4 solution Used with a template (e.g., Anodic Aluminum Oxide or Polycarbonate membrane)	Applied Voltage: 0.3−2.5 V Deposition Time: Up to 2 h Final Annealing: 485∘C	Arrays of single-crystalline nanorods Diameter: 100−200 nm Length: ≈10 µm	[10]

4. Role of Substrates in Nanorod Growth

4.1 Commonly used substrates (e.g., Si, glass, sapphire, FTO, ITO, Al_2O_3)

The substrate is very important for figuring out the shape, density, crystallinity, and direction of V_2O_5 nanorods. Nucleation and growth are controlled by things like lattice mismatch, surface energy, roughness, and chemical usefulness. These factors affect how well nanorods work in electrochemistry and optics.Conductive Substrates (ITO, FTO): Indium tin oxide (ITO) and fluorine-doped tin oxide (FTO) are commonly used in electrochromic and energy-storage devices because they make it easier for nanorods to line up vertically. For example, Tong and his colleagues reported that coralline V_2O_5 nanorods grown on ITO through annealing showed multicolor electrochromic behavior with a dyeing efficiency of 55 $cm^2\ C^{-3}$. This was made possible by the substrate's conductivity and the matching of the surface energy [3]. In the same way, ordered nanorods on FTO showed better charge transfer and stability in lithium-ion batteries, showing that the substrate can affect how things are arranged [36]. Figure 3 demonstrates the impact of various substrates on the development characteristics of V_2O_5 nanorods. On silicon and glass substrates, nanorods display arbitrary and disorganized orientations owing to inadequate lattice matching and amorphous surfaces. Sapphire (Al_2O_3) and FTO substrates facilitate vertically aligned and homogeneous nanorod development due to their crystalline structure and surface conductivity. Likewise, Al_2O_3 substrates facilitate the creation of dense and well-ordered nanorods owing to their advantageous lattice compatibility and oxygen-rich surfaces. The graphic illustrates that substrate selection significantly influences the alignment, density, and shape of V_2O_5 nanorods.

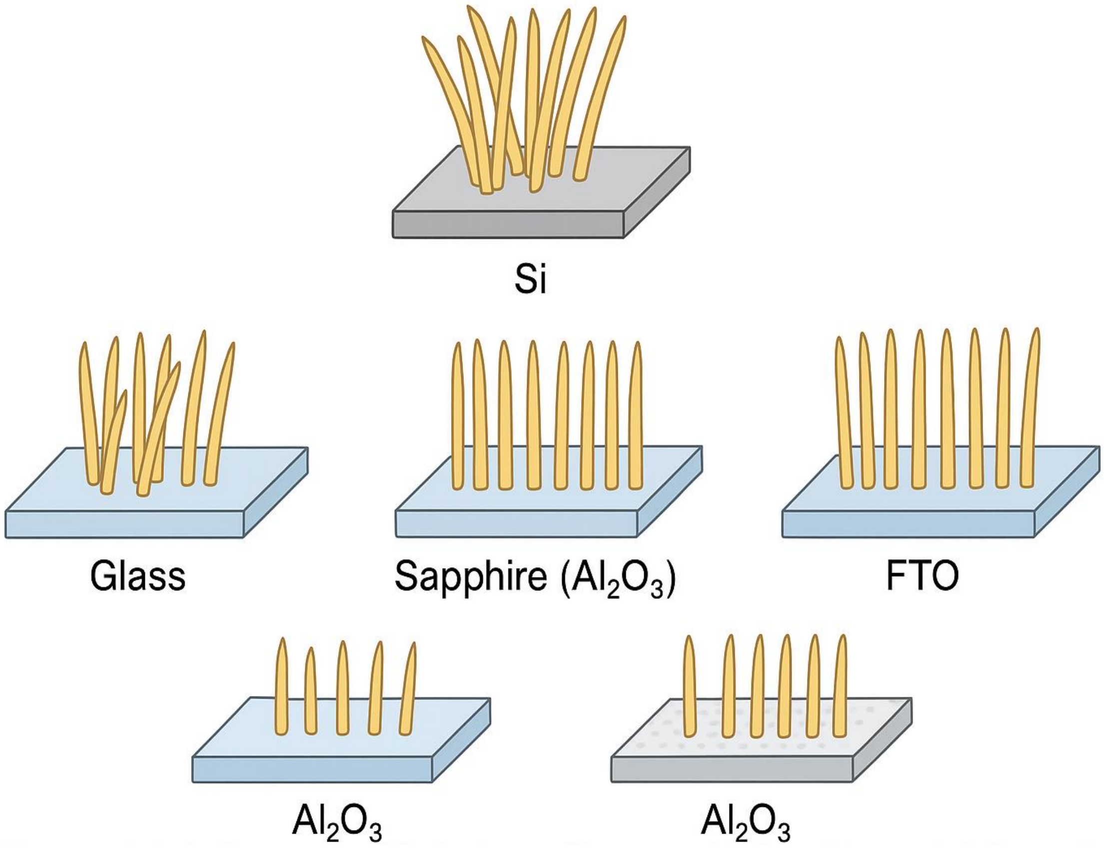

Figure 3: Impact of Substrate Type on V_2O_5 Nanorod Development

Semiconducting Substrates (Si): This type of material works best for heterojunction devices and integrating optics and electronics. Growth on Si(100) usually leads to nanorods with a fiber-like structure. On the other hand, epitaxial relationships between c-plane sapphire (Al_2O_3) and V_2O_5 can cause twin-domain epitaxy, which changes the crystallinity and flaw density [51]. It has been shown that the interface stretch and surface termination can directly change how light is absorbed and turned around in V_2O_5/Si heterojunctions [52]. Sapphire (Al_2O_3): Sapphire surfaces are very stable at high temperatures and have clear crystallographic planes, which lets vanadium oxides grow on top of them or almost on top of them. There is proof from experiments that c-Al_2O_3 encourages twin-domain epitaxy, which leads to high crystallinity but also defect-related strain. This kind of epitaxial control makes optical modulation better in vanadium oxides, which makes Al_2O_3 a useful base for tunable electro-optic uses [53].

Glass Substrates: Glass is still a cheap, flexible option that helps random nucleation and polycrystalline growth. Nanorods grown on glass often have less crystallinity and less alignment than epitaxial substrates. However, their surfaces can be more rough and porous, which is good for catalytic and sensing uses [54].

Comparative Studies: Looking at things directly across different surfaces shows how crystallinity and electrochemical performance are both good and bad. Liu and others showed that growing V_2O_5 on 3D ordered macroporous ITO made nanorods that were lined up vertically and had better cycle stability than those on glass. They stressed that the substrate's porosity and conductivity were the most important factors [28]. To sum up, conductive substrates like ITO and FTO help with vertical alignment and better electron transport. Si and sapphire substrates allow for epitaxial and heterojunction integration. Glass, on the other hand, allows for scaling but at the cost of alignment. So, changing the substrate through lattice matching, surface roughness, or porosity is a key part of making V_2O_5 nanorods work in devices that store energy, change color, or use light and electricity.

4.2 Substrate-lattice interactions and epitaxial relationships

The influence of substrates on the formation of V_2O_5 nanorods has garnered significant attention in recent years, particularly concerning lattice interactions and epitaxial relationships that determine morphology, crystallinity, and device efficacy. Substrate-lattice compatibility is essential for regulating the orientation and alignment of nanorods, as mismatched lattices may result in defects or strain relaxation events. Hydrothermally integrated V_2O_5 on microstructured silicon exhibited the wrapping of nanorods around the substrate, indicating that surface roughness significantly affects growth direction and charge-storage dynamics in energy applications [55]. Substrate chemistry and surface wettability significantly influence vanadia crystallization. Research on vapor transport growth has demonstrated that chemical interactions and lattice alignment at the interface affect epitaxial nucleation and morphology, highlighting that surface termination and oxide compatibility are equally important as geometric matching [56]. Pulsed laser deposition (PLD) of V_2O_5 on stainless steel revealed that substrate selection influences crystalline quality and phase stability, while post-annealing further alters nanorod alignment and morphology [57].

Substrate-induced epitaxial alignment has been demonstrated in the conversion of V_2O_5 thin films into VO_2 microrods, where epitaxial relationships formed during reduction resulted in ordered arrays with optical characteristics dependent on size. The findings indicate that the initial lattice-substrate compatibility of V_2O_5 establishes the foundation for further functional phase shifts [58]. Recent study highlights that substrate–lattice interactions influence epitaxial growth and nanorod alignment, while also modulating physical attributes like as conductivity, optical responsiveness, and electrochemical performance. For review purposes, novel methodologies focus on customizing substrate crystallography, chemistry, and morphology to achieve epitaxial control for the fabrication of high-quality V_2O_5 nanostructures in advanced devices.

4.3 Effect of surface energy, roughness, and functionalization

The surface energy, roughness, and functionalization of substrates are critical factors that influence the nucleation density, orientation, and morphology of V_2O_5 nanorods. Substrates with elevated surface energy facilitate nucleation by reducing the barrier for adatom attachment, resulting in dense and vertically oriented nanorod arrays. Oxygen vacancy engineering has been demonstrated to enhance surface energy, therefore facilitating ion intercalation and structural stability in V_2O_5 systems [59]. Recent investigations expand this to superhydrophobic and chemically modified surfaces, where functionalization with silicone-derived coatings optimized nanowire alignment and enhanced resilience against environmental degradation[60].Surface roughness serves as a template by offering favorable nucleation sites. Ion implantation research revealed that textured silicon substrates result in fractal-like growth of V_2O_5 thin films with modified wettability, highlighting that surface roughness influences both the thermodynamics and kinetics of nanorod formation [61].

Traditional wet-etching methods that promote pit formation on silicon have been demonstrated to facilitate regulated nucleation and alignment of vanadium oxide nanowires, suggesting that surface morphology significantly influences nanorod density and orientation [62]. The functionalization of substrates has evolved as a method to modify interfacial chemistry and facilitate regulated development. The incorporation of graphene oxide with hydrated V_2O_5 films, succeeded by photothermal modification, enabled precise adjustment of surface states and nucleation behavior by localized functionalization [63]. V_2O_5 nanorod/graphene oxide nanocomposites also benefited from percolative networks formed via surface functionalization, resulting in improved stability and electrochromic switching performance [64]. The maximizing surface energy, engineering nanoscale roughness, and implementing chemical functionalization are synergistic strategies that enable researchers to control nucleation density, epitaxial alignment, and the overall crystalline quality of V_2O_5 nanorods. These insights facilitate the customization of growth for particular optoelectronic, catalytic, and energy-storage applications.

4.4 Comparative studies: substrate dependence on orientation, density, and morphology

The production of vanadium pentoxide (V_2O_5) nanorods (NRs) has attracted a lot of attention because of its possible uses in optoelectronics, energy storage, and catalysis. The structural orientation, density, and shape of V_2O_5 NRs are significantly influenced by the substrate they are formed on. New research has shed light on the ways in which various substrates affect these characteristics.The substrate selection has a major impact on the crystallographic orientation of V_2O_5 NRs. For example, X-ray diffraction (XRD) patterns demonstrating strong peaks at $2\theta = 20.23°$, $26.29°$, and $27.78°$, corresponding to the (001), (110), and (101) planes, respectively, demonstrate that V_2O_5 NRs grown on glass substrates display a preferred orientation along the (001) plane [24]. This orientation is explained by glass's low surface energy, which encourages nanorod growth along the c-axis. On the other hand, because of their higher surface energies and possible lattice incompatibilities with V_2O_5, substrates such as silicon (Si) and indium tin oxide (ITO) may result in less noticeable orientation.Additionally, the form and density of V_2O_5 NRs depend on the substrate. A high density of nanorods with diameters between 40 and 60 nm and lengths between 400 and 600 nm is produced on glass surfaces due to homogeneous nucleation made possible by the low surface energy [24]. On ITO substrates, on the other hand, the higher surface energy and possible flaws result in more irregular morphologies and a lower density of nanorods. These morphological variations have been clarified in large part by examinations using scanning electron microscopy (SEM) and field emission scanning electron microscopy (FESEM).The sol-gel production of V_2O_5 nanorods using citric acid, ethylene glycol, and ammonium metavanadate in DI water, followed by evaporation, heating, and calcination, is depicted in this image 4. TEM analysis of the resultant nanorods, which are about 50 nm in size, reveals their crystalline structure and orientation along the (001) plane. Cyclic voltammetry (CV) and cycling stability experiments are used to assess electrochemical performance, demonstrating the nanorods' potential for energy storage applications with high electrochemical activity and capacitance retention [65].

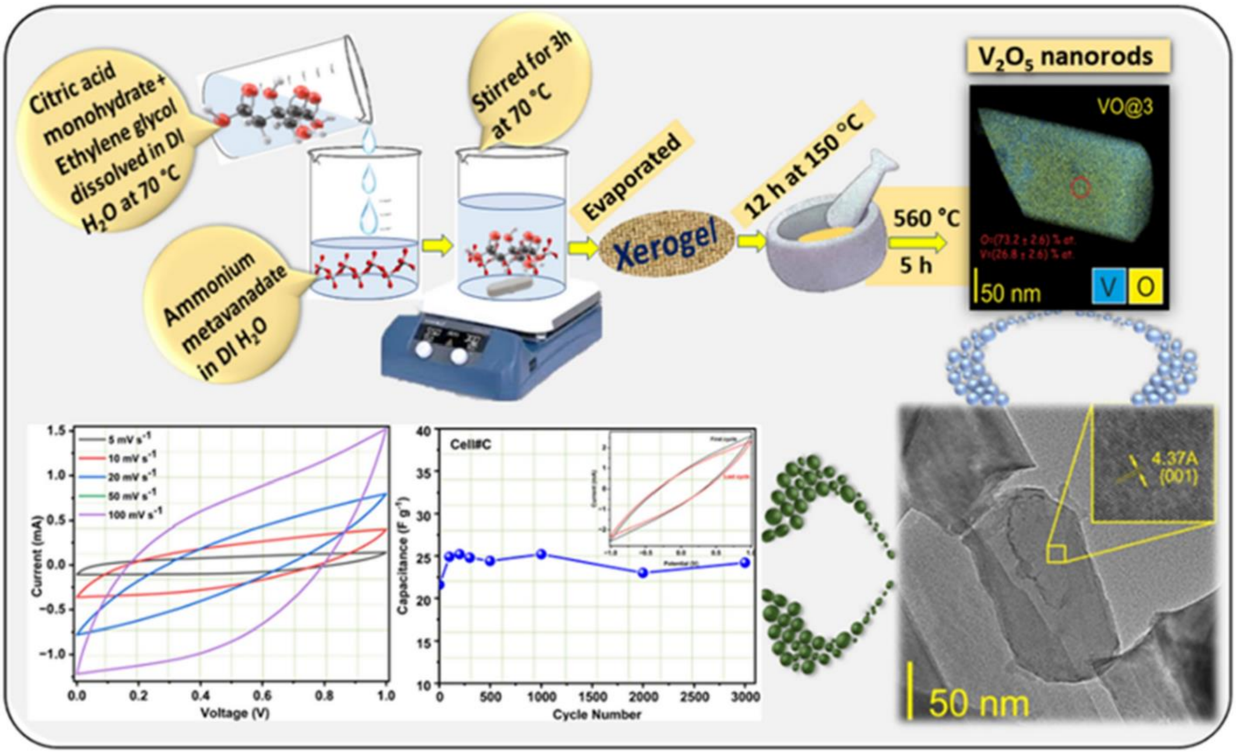

Figure 4: Synthesis and electrochemical performance of V_2O_5 nanorods prepared via a sol–gel route [65]

The substrate has an impact on the crystallinity and morphology of V_2O_5 NRs, which in turn affect their optical characteristics. V_2O_5 NRs grown on glass substrates display Raman peaks at 143 cm^{-1}, 694 cm^{-1}, and 993 cm^{-1}. These peaks correspond to the edge-shared oxygen modes, V_2O stretching modes, and the B_3g mode of V–O–V chains, respectively [24]. A well-ordered structure, which supports improved electrical characteristics, is indicated by these peaks. For V_2O_5 NRs on glass substrates, ultraviolet-visible (UV-Vis) absorption spectra further show a blue shift in the absorption edge, indicating a decrease in the bandgap and enhanced electronic conductivity.Substrate effects on V_2O_5 NRs have been well understood thanks to recent research. The impact of different substrates on the structural integrity, phase purity, morphology, composition, magnetic properties, and electronic behavior of V_2O_5 thin films grown on Si (111), ITO-coated glass, and glass substrates, for instance, is highlighted in a 2025 study [66]. This work emphasizes how crucial substrate selection is to customizing V_2O_5-based materials' characteristics for particular uses.The orientation, density, and shape of V_2O_5 nanorods, and consequently their optical and electrical characteristics, are all significantly influenced by the substrate selection. It is crucial to comprehend these substrate-dependent properties in order to optimize the synthesis of V_2O_5 NRs for a range of technological applications.A comparative review of the role of substrates in V_2O_5 nanorod growth is given in Table 2, which also describes how various substrate types affect the properties of the final nanostructure. Role of particular substrate (e.g., Si(001), Glass, ITO) and the synthesis method (e.g., Thermal Oxidation, Hydrothermal, Vapor-Solid) have been compared. In order to highlight that high roughness and amorphous surfaces usually result in a higher density of nanorods due to increased nucleation sites, key experimental observations are categorized according to the substrate's Influence/Parameter (such as thermal conductivity, surface roughness, or amorphous nature), the resulting nanorod Orientation/Epitaxy (most often the preferred (001) plane or single-crystalline growth), and the final Morphology/Density.

Table 2: V_2O_5 Nanorod Orientation, Morphology, and Density Affected by Synthesis Method and Substrate Properties (such as roughness and thermal conductivity)

Synthesis Method	Substrate	Key Substrate Influence/Parameter	Nanorod Orientation/Epitaxy	Morphology/Density	Reference
Thermal Oxidation (of V2 O3 thin film)	Si(001) wafer	Good thermal conductivity and lattice mismatch	Single-crystalline V2O5 nanorods (Orthorhombic phase)	Uniform-sized nanorods formed. High thermal conductivity helps in uniform heating, leading to better-defined nanorods.	[31, 67]
Hydrothermal Method	Si(100)	Native Oxide Layer (SiO2) creates an amorphous surface for nucleation.	Preferred orientation (001) plane for the V2O5 nanorods.	Good coverage, V2 O5 nanorods.	[24]
	Glass (Amorphous)	Amorphous surface allows random nucleation. Lower thermal conductivity compared to Si.	V2O5 primarily oriented along (001).	Higher density of nanorods observed compared to Si and ITO, likely due to a larger number of random nucleation sites on the amorphous surface.	[24]
	ITO (Indium Tin Oxide)	Crystalline structure (polycrystalline) with moderate thermal conductivity.	V2O5 primarily oriented along (001).	Nanorod coverage is less dense compared to Glass. Substrate structure influences film homogeneity.	[24]
Vapor-Solid (VS) Method / CVD	Si and FTO (Fluorine-doped Tin Oxide) Glass	Surface Energy and Supersaturation of VOx vapor.	Highly Crystalline 1D V2O5 nanorods.	Highly Crystalline nanorods achieved on both, suggesting the V2O5 phase is stable across these common materials.	[68]
Wet Chemical/Thermal Evaporation	Rough Si (Porous Si)	Increased Surface Roughness and high density of nucleation sites (pit areas).	Orthorhombic structure with (001) out-of-plane orientation.	Increased number density and aspect ratio of V2O5 nanowires/nanorods compared to flat Si.	[62]

5. Effect of Thermal Annealing

Thermal annealing substantially affects the crystallinity of V_2O_5 thin films. With an increase in annealing temperature, the films undergo a transformation from an amorphous to a polycrystalline structure. X-ray diffraction (XRD) investigation demonstrates the appearance of distinct peaks associated with the (110) and (020) planes of V_2O_5 at around 400°C, signifying enhanced crystallinity [69]. Excessive annealing temperatures can result in the production of elevated oxidation states, such as V_6O_{18}, potentially compromising the electrochromic performance of the films [70]. Thermal annealing induces phase changes in V_2O_5 films from an amorphous state to an orthorhombic crystalline structure. This transition is vital for applications such as electrochromic devices, where the material's capacity for reversible redox reactions is imperative. The orthorhombic phase has superior electrochemical stability and enhanced coloring efficiency relative to its amorphous counterpart [69]. The V_2O_5 thin film's XRD spectrum is seen in Figure5 following thermal annealing at 200, 300, and 400 °C, respectively. The samples that were annealed at 200 and 300 degrees Celsius have an amorphous spectrum. There was no diffraction peak found in the XRD investigation. Two diffraction peaks were found in the V_2O_5 thin film when the annealing temperature rose to 400 °C. At 2θ values of 26.3° and 50.5°, two reflection peaks were detected, which corresponded to orthorhombic structure reflections of (110) and (020). This result indicates that following the 400 °C thermal annealing, the V_2O_5 thin film underwent a new phase of polycrystalline growth [69].

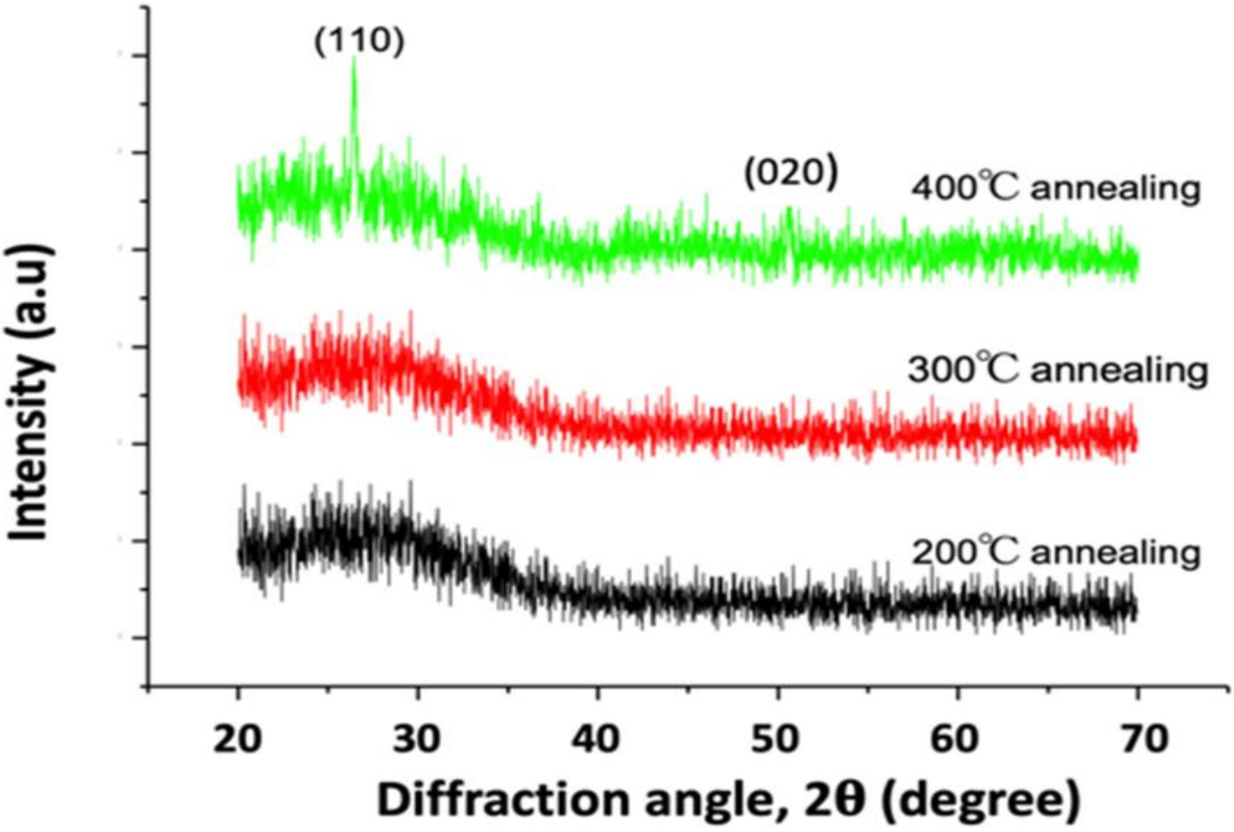

Figure 5: The XRD patterns of V_2O_5 thin films post-thermal annealing at 200, 300, and 400 °C, respectively [69]

The annealing process, particularly in decreasing atmospheres or inert gases such as argon, can create oxygen vacancies in V_2O_5 films. These vacancies are crucial in adjusting the electrical characteristics of the material. X-ray photoelectron spectroscopy (XPS) investigations have demonstrated that annealing in an argon atmosphere results in a decrease in the V $2p_{3/2}$ binding energy, signifying an augmentation of oxygen vacancies [71]. Furthermore, reactive oxygen annealing (ROA) has been investigated as a technique to effectively modify the oxidation states of vanadium oxide films at lower temperatures, providing a means for stoichiometric adjustment Reference [72]. Thermal annealing facilitates grain formation in V_2O_5 thin films, hence improving their mechanical and electrical properties. Scanning electron microscopy (SEM) photographs indicate that with an increase in annealing temperature, both the grain size and surface morphology exhibit an enhancement in smoothness [69]. The grain growth is linked to the repair of structural flaws, resulting in enhanced crystallinity and possibly superior performance in applications such as sensors and electrochromic devices.

The selection of substrate markedly influences the annealing characteristics and resulting properties of V_2O_5 films. For example, films formed on silicon substrates may have varying thermal stability and phase transition temperatures in comparison to those on glass or sapphire substrates [73]. The coefficients of thermal expansion and surface energy of the substrate can affect the stress and strain in thin films during annealing, thereby impacting their structural integrity and performance in device applications.Thermal annealing is an essential procedure for modifying the structural and functional characteristics of V_2O_5 thin films. By meticulously regulating the annealing temperature and environment, one may maximize crystallinity, induce specific phase transitions, adjust oxygen vacancies, and augment grain size, all of which are crucial for the efficacy of V_2O_5-based devices across diverse applications.

6. Applications Influenced by Substrate & Annealing

Thin films of vanadium pentoxide (V_2O_5) show exceptional adaptability in a variety of energy and sensing applications. Their structural, electrical, and optical characteristics are greatly influenced by the substrate selection and thermal annealing conditions, which allows for customization of their performance for particular technologies. Annealing procedures that improve crystallinity and conductivity in V_2O_5 films in lithium-ion batteries and supercapacitors improve charge/discharge cycles and capacitance retention [69]. The porous morphology produced by optimal annealing allows for greater surface area and active sites, which improves sensitivity and reaction times for gas sensors, especially those that detect ammonia [74]. The annealing temperature has an impact on the photocatalytic efficiency of V_2O_5 in solar cells and photocatalysis. This temperature also impacts the band gap and charge carrier dynamics of the film, which optimizes light absorption and electron-hole pair separation [75]. When exposed to particular annealing conditions that encourage the production of desirable crystalline phases and grain sizes, electrochromic devices made from V_2O_5 thin films exhibit improved coloration efficiency and switching times [70]. The microstructure, porosity, and electronic characteristics of the film are determined by the interaction between the substrate material and annealing settings, which ultimately determines the film's applicability and performance in these cutting-edge applications.Figure 6shows the impact of substrate selection and heat annealing on V_2O_5 nanostructures and their applications. V_2O_5 nanorods or nanosheets crystallinity, morphology, defect density, and alignment are influenced by substrates like FTO, ITO, sapphire, and silicon, as well as regulated annealing temperatures. These tailored nanostructures are then used in a variety of applications, including enhanced lithium-ion batteries and supercapacitors with improved ionic and electronic transport, gas sensors with increased sensitivity and selectivity, photocatalysis and solar cells with optimized light absorption and charge carrier dynamics, and electrochromic devices with superior color-switching efficiency and durability. The diagram visualizes the relationship between synthesis parameters and functional performance of V_2O_5 for energy and sensing applications, including substrate and annealing properties.

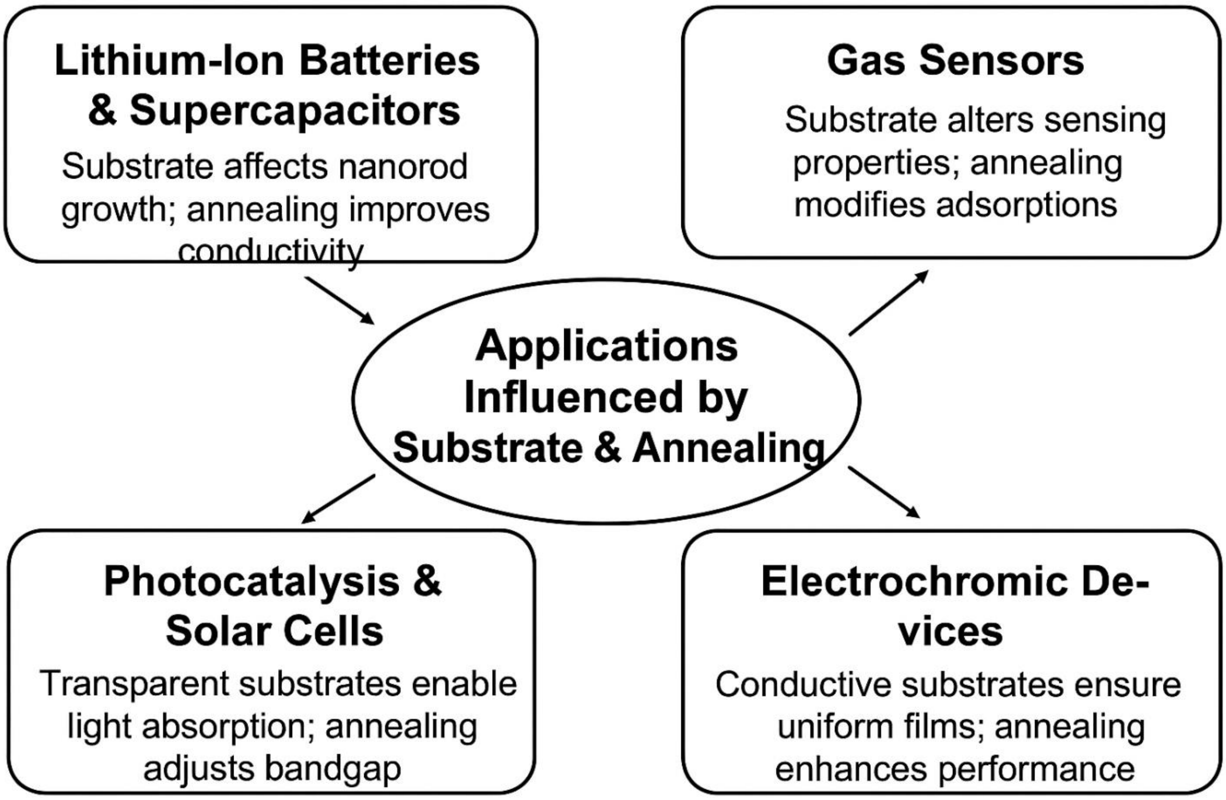

Figure 6: Schematic depicting the impact of substrate selection and thermal annealing on V_2O_5 nanostructures and their potential applications in electrochromic devices, sensing, photocatalysis, and energy storage

6.1 Lithium-ion batteries and supercapacitors

Vanadium pentoxide (V_2O_5) has attracted considerable interest as an electrode material in lithium-ion batteries (LIBs) and supercapacitors owing to its elevated theoretical capacity and stratified architecture. Nonetheless, its actual implementation is frequently impeded by issues like as inadequate electrical conductivity and structural instability. Recent investigations have shown that the selection of substrate and annealing conditions are crucial for improving the electrochemical performance of V_2O_5-based electrodes.The electrochemical performance of V_2O_5 cathodes in LIBs is affected by the substrate material, which influences film morphology and adhesion. Research indicates that V_2O_5 thin films applied to diverse substrates demonstrate varying capabilities and cycle stabilities. The annealing operations further alter the crystallinity and phase composition of V_2O_5, resulting in enhanced capacity retention and rate capability. Annealing at temperatures between 300–400°C has been shown to improve the electrochemical performance of V_2O_5 electrodes in lithium-ion batteries [76]. The electrochemical performance of V_2O_5 electrodes in supercapacitors is similarly affected by substrate choice and annealing parameters [65]. The selection of substrate influences the porosity and surface area of the V_2O_5 films, which are essential for charge storage. Annealing treatments can provoke phase transitions and structural alterations that improve capacitive performance. For instance, β-V_2O_5 films subjected to annealing at 300°C exhibit reduced charge transfer resistance and enhanced capacitance [77]. These findings emphasize the necessity of modifying substrate materials and annealing conditions to improve the electrochemical performance of V_2O_5-based electrodes in energy storage applications.

6.2 Gas sensors

Vanadium pentoxide (V_2O_5) has emerged as a viable material for gas sensors owing to its elevated surface area, adjustable electrical characteristics, and catalytic efficacy. The efficacy of V_2O_5-based gas sensors is markedly affected by the selection of substrate and subsequent annealing processes.The substrate material influences the adhesion, shape, and crystallinity of V_2O_5 films, therefore affecting their gas sensing characteristics. For instance, V_2O_5 thin films applied to glass substrates using spray pyrolysis demonstrate enhanced gas sensing responses relative to those put on alternative substrates. The distance between the nozzle and substrate during deposition is critical in influencing the film's microstructure and, subsequently, its gas sensing efficacy [78]. Post-deposition annealing treatments are utilized to improve the crystallinity and phase purity of V_2O_5 films, which are crucial for good gas sensing efficacy. Annealing at around 500°C has demonstrated enhancement in the sensitivity of V_2O_5-based sensors to gases such as NO_2 [79]. The annealing procedure can impact the transition between p-type and n-type semiconducting activity in V_2O_5, hence influencing the sensor's responsiveness to various gases [80]. Both the substrate material and annealing conditions are crucial elements that affect the structural characteristics and gas sensing efficacy of V_2O_5-based sensors. Enhancing these parameters can result in substantial advancements in sensor sensitivity, selectivity, and stability, rendering V_2O_5 a suitable choice for diverse gas sensing applications.

6.3 Photocatalysis and solar cells

Vanadium pentoxide (V_2O_5) has attracted considerable interest in photocatalysis and solar cell applications owing to its advantageous electrical structure and adjustable characteristics. The efficacy of V_2O_5 in various applications is significantly affected by substrate choice and annealing parameters, which influence its crystallinity, shape, and electronic properties.In photocatalytic applications, V_2O_5 has proven effective in environmental cleanup, particularly in the breakdown of organic contaminants. The photocatalytic efficacy of V_2O_5 is markedly improved through the optimization of synthesis techniques and subsequent post-deposition processes. The integration of rare-earth ions such as Holmium (Ho) and Ytterbium (Yb) into V_2O_5 has demonstrated enhanced photocatalytic efficiency, with degradation rates of up to 95% under visible light irradiation [81]. The composition and construction of a flexible organic solar cell with a hydrated vanadium oxide (V_2O_5-w) layer are depicted in the figure 7. A bottom FLEXTRODE made of Ag‖PEDOT‖ZnO, an active P3HT:PCBM photoactive layer, a V_2O_5-w hole transport layer, and an Ag grid top electrode make up the device, which is constructed on a PET substrate. The reversible dehydration process of $V_2O_5 \cdot 1.6H_2O$ to $V_2O_5 \cdot 0.5H_2O$ at 120 °C is depicted in the schematic on the right, demonstrating the structural and chemical versatility of the vanadium oxide interlayer. Flexible solar cell devices with an active area of 1 cm^2 are shown in the inset photo, showcasing their mechanical adaptability and promise for a variety of photovoltaic applications [82].

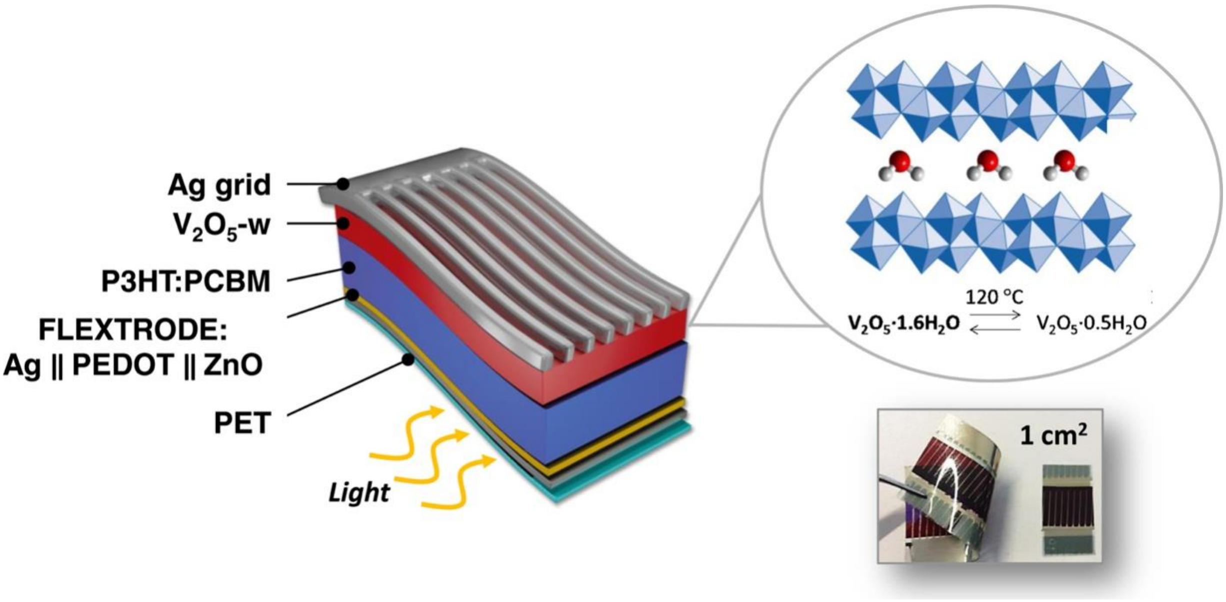

Figure 7: A flexible organic solar cell design with a V_2O_5-w interlayer [82]

The synthesis temperature is critical; V_2O_5 produced at lower temperatures demonstrates a reduced bandgap and enhanced photocatalytic efficiency relative to that synthesized at elevated temperatures [83]. In the domain of solar energy, V_2O_5 functions as an efficient hole transport layer (HTL) in several photovoltaic devices. Its function is to enable hole extraction while reducing recombination losses. Research has shown that solution-processed V_2O_5 can serve as a hole transport layer in CuO-ZnO-based solar cells,resulting in enhanced device performance [84]. Moreover, V_2O_5 has been employed in all-inorganic Sb_2S_3 solar cells, substituting conventional organic hole transport layers, thus improving device stability and efficiency [85]. The selection of substrate and annealing parameters is crucial in customizing the characteristics of V_2O_5 films for particular applications. Annealing at temperatures between 300–400°C can enhance the crystallinity and electronic characteristics of V_2O_5 films, consequently improving their photocatalytic and photovoltaic performance[69]. The substrate material influences the adherence and shape of V_2O_5 films, hence affecting their overall performance in device applications [86]. V_2O_5 demonstrates significant potential in photocatalysis and solar cell applications. Enhancing the performance of V_2O_5-based devices can be achieved by the optimization of synthesis methods, doping tactics, substrate selection, and annealing conditions, hence facilitating more efficient and sustainable energy solutions.

6.4 Electrochromic devices

Vanadium pentoxide (V_2O_5) has surfaced as a viable material for electrochromic (EC) devices owing to its significant optical contrast, rapid switching times, and capacity for multicolor applications. The electrochromic performance of V_2O_5 is markedly affected by substrate selection and post-deposition annealing conditions, which alter its structural, optical, and electrochemical characteristics.The substrate material is essential for the nucleation and development of V_2O_5 thin films. Research indicates that substrates with varying surface energies might result in differences in the morphology and crystallinity of V_2O_5 films, thus affecting their electrochromic properties. Substrates such as indium tin oxide (ITO) glass are frequently employed because of their transparency and electrical conductivity, enabling the production of transparent electrochromic devices. The interaction between the substrate and the V_2O_5 film might affect the film's adherence, homogeneity, and overall efficacy in electrochemical applications [86]. Figure8 displays 3D surface topography images of thin films captured using Atomic Force Microscopy (AFM). These images typically illustrate the evolution of the surface morphology of a material (e.g., V_2O_5 or metal oxide thin films) through various synthesis or annealing processes Reference [69].

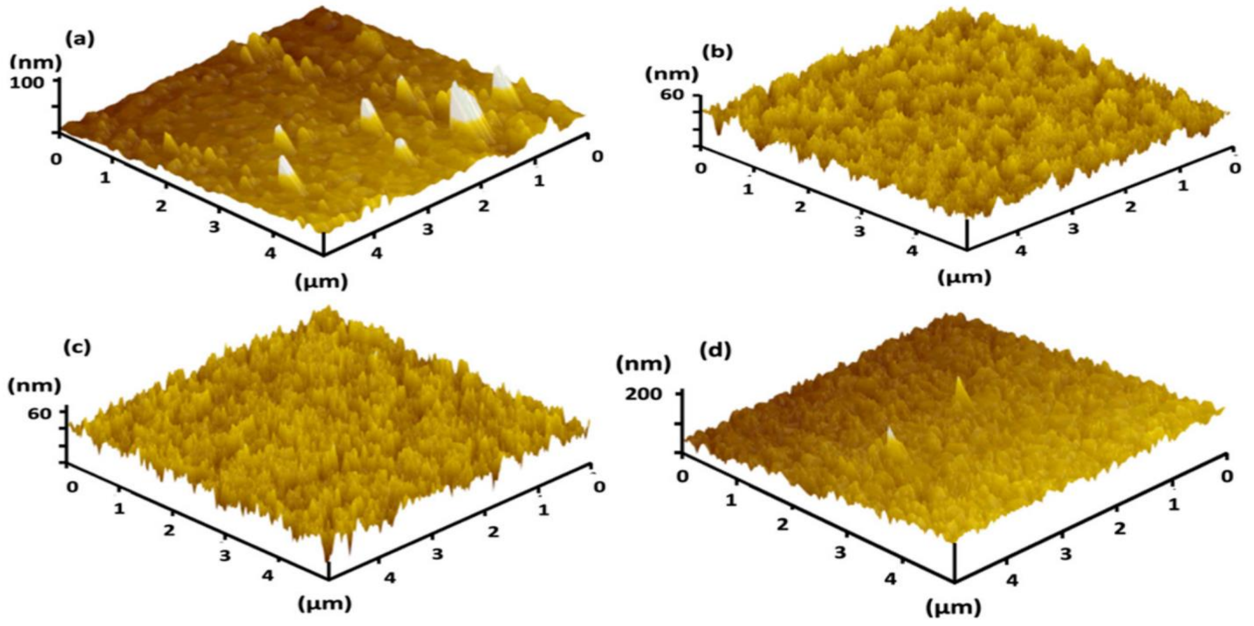

Figure 8: Three-dimensional AFM images of V_2O_5 thin films: (a) unannealed, (b) annealed at 200 °C, (c) annealed at 300 °C, and (d) annealed at 400 °C [69]

Post-deposition annealing is an essential procedure that improves the crystallinity and electrochemical characteristics of V_2O_5 films. Annealing at around 200°C has been documented to enhance the optical contrast and coloration efficiency of V_2O_5-based electrochromic devices. V_2O_5 films annealed at 200°C demonstrated an optical contrast of 42.32%, a coloration efficiency of 34.93 cm^2/C, and swift switching speeds of 0.4 s for coloration and 3 s for bleaching. Conversely, elevated annealing temperatures, such as 300°C, resulted in diminished optical modulation and coloration efficiency, underscoring the necessity of adjusting annealing conditions for optimal electrochromic performance [70]. The electrochromic characteristics of V_2O_5 are closely associated with the selection of substrate and annealing parameters. By meticulously choosing substrates and fine-tuning annealing temperatures, one may customize the structural and electrochemical properties of V_2O_5 films, thus improving the efficacy of electrochemical devices. Ongoing research in this domain is crucial for the advancement of efficient, durable, and scalable electrochromic technologies.

6.5 Correlation between synthesis-annealing-substrate and performance

The efficacy of vanadium pentoxide (V_2O_5) in diverse applications is closely associated with the synthesis techniques, annealing procedures, and substrate selections. Comprehending the relationships among these parameters is essential for enhancing V_2O_5-based devices.The synthesis method greatly affects the structural and morphological characteristics of V_2O_5 films.Techniques include sol-gel spin coating, thermal evaporation, and spray pyrolysis each confer unique properties to the films. For example, sol-gel spin coating can yield films with regulated thickness and homogeneity, whereas thermal evaporation may produce films with varying grain sizes and orientations. These differences can influence the material's electrical and opticalcharacteristics, consequently affecting device performance [86]. Post-deposition annealing is an essential process that can improve the crystallinity and phase purity of V_2O_5 films. Annealing temperatures and durations must be meticulously regulated, as they can affect the oxidation state of vanadium, grain size, and surface shape. Annealing at approximately 200°C has been demonstrated to enhance the electrochromic performance of V_2O_5 devices, but elevated temperatures may result in deterioration [70]. The selection of substrate influences the adhesion, shape, and electrical characteristics of V_2O_5 films. Substrates such as glass, silicon, and indium tin oxide (ITO) are frequently utilized, each presenting distinct benefits. ITO substrates have excellent conductivity and transparency, rendering them appropriate for optoelectronic applications. The contact between the substrate and the V_2O_5 film might alter the film's stress, thus affecting its mechanical stability and performance [86]. The interaction of synthesis techniques, annealing procedures, and substrate choices dictates the ultimate characteristics of V_2O_5 films. Refining these characteristics can result in improved performance in applications like lithium-ion batteries, supercapacitors, gas sensors, photocatalysis, solar cells, and electrochromic devices.In electrochromic devices, the coloration efficiency and switching periods are determined by the crystallinity and morphology of the V_2O_5 film, which are regulated by the synthesis and annealing conditions [70].

In order to customize materials for particular uses, it is crucial to have a thorough grasp of how different synthesis methods, annealing procedures, and substrate choices impact the characteristics and functionality of V_2O_5 films. In order to create V_2O_5based systems that are more efficient and dependable, future studies should methodically investigate these associations.

7. Challenges and Future Perspectives

The synthesis and characterization of V_2O_5 nanorods during thermal annealing present both promising future directions and scientific challenges. The morphology and crystallinity of V_2O_5 nanorods are significantly influenced by the substrate surface energy, lattice mismatch, and annealing temperature, making uniformity across substrates a critical limitation. Studies conducted by Raman andKumar have shown that the electrical uniformity of substrates such as Si, ITO, and glass can be influenced by temperature variations during annealing, which can lead to inconsistent rod lengths and aspect ratios throughout the substrate. It is challenging to obtain consistent film coverage and crystallographic orientation, which are essential factors for the reproducibility of optoelectronic devices, due to the fact that surface diffusion and grain boundary mobility vary depending on the substrate type [9, 29]. Another significant impediment to large-scale deployment is scalability. Although hydrothermal and sol–gel routes are well-established, they are frequently constrained by the size of the sample and the reproducibility of the process. Progress toward gram-scale production has been achieved through the implementation of microwave-assisted synthesis and spray pyrolysis[26].However, the maintenance of phase integrity and crystallographic control during scale-up remains a significant challenge. Continuous-flow or chemical vapor deposition (CVD)-based methods are currently being investigated for industrial applications;

however, their high energy requirements and equipment costs present obstacles to commercialization [87]. Another urgent concern is the stability of nanorods in operational environments, particularly in photovoltaic and electrochromic devices. Oxygen vacancy migration, phase transitions, and structural degradation can be induced by thermal cycling and high bias operation [3]. Tong have reported that the electrochromic efficiency of V_2O_5 nanorods on ITO substrates decreases after prolonged cycling, which is ascribed to vanadium reduction ($V^{5+} \rightarrow V^{4+}$). In the same vein, Sahoo noted that performance decay occurs as a result of microstructural strain in post-annealed V_2O_5 nanostructures when subjected to high-current stress [88]. In the future,there are numerous potential research directions. The V_2O_5 lattice can be stabilized and electronic conductivity can be enhanced by adjusting the oxygen vacancy concentration through doping with elements such as W, Ti, or Mo. [16] Heterostructures, including V_2O_5–ZnO composites, exhibit improved charge transport and photoresponse properties, which offer potential for multifunctional optoelectronic and sensing applications [89]. Furthermore, the technical challenge of maintaining adhesion and conductivity at low annealing temperatures persists, despite the fact that flexible substrates such as polyimide and PET are being investigated to facilitate the development of flexible and wearable electronics [90]. Lastly, in-situ annealing techniques are proposed to accomplish real-time crystallization and stress relief during device fabrication, resulting in improved morphology and phase control without the need for additional post-processing [91]. These techniques utilize controlled thermal ramps.Collectively, despite the significant progress that has been made in the synthesis of high-quality V_2O_5 nanorods with tunable properties, the cornerstone for future breakthroughs in vanadium oxide–based electronics and photonics is the achievement of substrate-independent uniformity, scalable production, and long-term stability under device operation.

8. Conclusion

The morphology, crystallinity, and optoelectronic behavior of vanadium pentoxide (V_2O_5) nanorods are significantly influenced by the substrate selection, as demonstrated by the fabrication and characterization of these nanorods under thermal annealing conditions. Substrates such as Si, glass, ITO, FTO, and Al_2O_3 have exhibited a substantial impact on the formation of grain boundaries, crystal orientation, and nucleation density in various studies. The annealing temperature and atmosphere (air, O_2, or inert) are also critical parameters that regulate the oxidation states (V^{5+}/V^{4+} ratio) and defect densities of V_2O_5 nanorods. These parameters, in turn, influence the electrochemical activity, photoluminescence, and electrical conductivity of the nanorods.

In general, annealing at temperatures exceeding 400 °C induces a transition from amorphous to highly crystalline orthorhombic V_2O_5, thereby improving structural stability and carrier mobility. Orientation-specific growth can be induced by substrate-dependent stress and lattice mismatch (e.g., (001) planes on FTO), while glass and Si substrates frequently produce arbitrarily oriented nanorods. The superior performance of substrate-engineered V_2O_5 nanorods in Li-ion intercalation, photocatalysis, and gas sensing is consistently demonstrated by studies, which are attributable to the enhanced electronic pathways and surface-to-volume ratios. In general, it is imperative to optimize the interaction between precursor chemistry, annealing conditions, and substrate type in order to customize the desired properties of V_2O_5 nanostructures. In order to develop V_2O_5 nanorod systems that are both reproducible and application-specific, future research should concentrate on in-situ growth monitoring, interface engineering, and defect modulation.

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