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Vanadium Pentoxide (V_2O_5): Their Obtaining Methods and Wide Applications

Dane Tadeu Cestarolli and Elidia Maria Guerra

Abstract

The first synthesis of pentoxide vanadium (V_2O_5) as gel completed 135 years in 2020. Since its first synthesis, the V_2O_5 has attracted attention over the years in different areas in science and technology. There are several possibilities to obtain V_2O_5 resulting in different structures. Among these methods, it is possible to mention the sol-gel, hydrothermal/solvothermal synthesis, electrospinning, chemical vapor deposition (CVD), physical vapor deposition (PVD), template-based methods, reverse micelle techniques, Pechini method and electrochemical deposition that can be considered as the great asset for its varied structures and properties. Progress towards obtaining of different structures of V_2O_5 , and phases have been resulted in lamellar structure with wide interlayer spacing, good chemical and thermal stability and thermoelectric and electrochromic properties. Throughout this advancement, its performance for industrial applications have made a strong candidate in electrochromic devices, photovoltaic cell, reversible cathode materials for Li batteries, supercapacitor, among others. This chapter will be to assist an updated review since the first synthesis up to current development.

Keywords: V_2O_5 , obtaining methods, structures, applications

1. Introduction (Historical and sources)

The discovery of vanadium was marked by uncertainty and confusion due to its chemical similarity with some elements. In 1801, the Spanish mineralogist, Andrés Manuel Del Rio, discovered an element with the atomic number 23, in Mexico, in a lead mineral. Due to the similarity of its colors to those of chrome, Del Rio called this element as panchrome. Later, after noting that the color of these salts turned red when heated, he renamed it as erythron. However, Del Rio withdrew his claim when, four years later, it was suggested by the French chemist, Hippolyte Victor Collett-Desotils, that the mineral was really an impure chromium, provoking the retraction of Andrés Manuel Del Rio [1]. In 1830, Swedish chemist Nils Gabriel Sefström rediscovered the element in an oxide that it was found while working at an iron mine and gave it the name by which it is known today. A year later, in 1831, Friedrich Woehler confirmed that this element was the same already discovered by Del Rio in 1801. In 1867, Henry Enfield Roscoe, an English chemist, isolated it almost purely by reducing the chloride with hydrogen [1]. The name vanadium refers to the goddess of beauty in Scandinavian mythology Vanadis, also known as Freya, due to the beautiful variation in the color of its compounds. Vanadium

is the nineteenth most abundant element in the earth's crust (136 ppm), and the fifth among transition metals. Despite being a metal considered abundant, it is not found in its elemental form, but it is present in approximately 65 different minerals, among which stand out vanadinite, $\text{PbCl}_2 \cdot 3\text{Pb}_3(\text{VO}_4)_2$, carnotite, $\text{K}_2(\text{UO}_2)_2(\text{VO}_4)_2 \cdot 3\text{H}_2\text{O}$, roscoelite $\text{K}(\text{V}_3\text{AlMg})_2(\text{SiAl})_4\text{O}_{10}(\text{OH})_2$ and patronite, V_2S_3 [2]. Of the world's vanadium resources, most are present in magma, located in the Bushveld volcanic complex in South Africa, which has the world's largest reserves of iron/vanadium, followed by Russia, the United States and China. In 2019, about 90% of vanadium was obtained from magnetite and titanomagnetite ores. Regarding vanadium production, China led the largest global production of 2019 through slag. Asia China is the world's largest producer of vanadium, with 59%, followed by Russia accounting for 17% and South Africa with 7% of the global supply of vanadium. Most of its vanadium was derived from the primary production of Bushveld Minerals and Glencore. The most commercially available vanadium products are vanadium pentoxide and iron-vanadium. Vanadium pentoxide is obtained by treating magnetite iron ores and slag.

2. Structures of vanadium oxides

The system of V-O has different oxidation states with V_2O_5 being the most stable. This system occurs from V^{2+} to V^{5+} such as vanadium monoxide (VO), vanadium sesquioxide (V_2O_3), vanadium dioxide (VO_2) and vanadium pentoxide (V_2O_5). Besides, it is possible to obtain mixed valence oxides that present several of oxides containing $\text{V}^{5+}/\text{V}^{4+}$ mixture (in V_3O_7 , V_4O_9 , and V_6O_{13}) and $\text{V}^{4+}/\text{V}^{3+}$ mixture (in V_6O_{11} , V_7O_{13} , and V_8O_{15}) [3]. From these mixing phases is possible to form two phases called as Magnéli phase ($\text{V}_n\text{O}_{2n-1}$) and Wadsley phase ($\text{V}_n\text{O}_{2n+1}$). A schematic V-O phase diagram calculated by Kang [4] presented the Magnéli phase as being V_6O_{13} , V_3O_7 , V_2O_5 as well as Wadsley phase V_3O_5 , V_4O_7 , V_5O_9 , V_6O_{11} , V_7O_{13} and V_8O_{15} . The phases and structures in the V-O phase diagram is depicted in **Table 1**.

From the **Table 1**, it is possible to observe that the V-O system can exhibit multiple crystalline structures. These crystalline structures can be modified considering the oxygen fractions in the range 0.5–0.75 and decrease of formation energy ($\text{eV} \cdot \text{atom}^{-1}$). It is worth mentioning that formation energy between the stable and metastable phases ranges, for example, between 4 meV in V_2O_5 and 35 meV in V_2O_3 , making possible a reversible structural transition [5]. The Magnéli phase ($\text{V}_n\text{O}_{2n-1}$, with $n = 4$ to 9) is considered as being rutile-type with VO_6 octahedral [6]. The increase of n in $\text{V}_n\text{O}_{2n-1}$ compounds might have an inherent effect on the magnetic and electric properties.

On the other hand, Wadsley phase, ($\text{V}_n\text{O}_{2n+1}$, with $n = 1$ to 6) is known as layered vanadium oxides. This V-O phase has single and double layers being able to accommodate V^{4+} cations and both $\text{V}^{4+}/\text{V}^{5+}$ cations, respectively [5, 7, 8]. The presence of these layers makes it possible to intercalate different ions which makes them suitable for energy conversion and storage [9]. Besides, mixed valence in Wadsley phase can be formed by introducing oxygen vacancy. The oxygen vacancy can generate mixed oxidation state with two oxidation states. It is possible to point out V_6O_{13} with $\text{V}^{5+}/\text{V}^{4+}$ as well as VO_2 , V_2O_3 , V_8O_{15} , V_7O_{13} , V_6O_{11} with $\text{V}^{4+}/\text{V}^{3+}$ species.

The most famous and stable of the layered $\text{V}_n\text{O}_{2n+1}$ is V_2O_5 . Along the xyz axis (3D) V_2O_5 presents a V chains forming a network with oxygen which results as VO_5 pyramids [6]. X-ray diffraction (XRD) pattern of orthorhombic V_2O_5 and a layered crystalline structure has a standard pattern number JCPDS No. 41–1426 [10]. That way, its structure is orthorhombic with parameters $a = 1.151 \text{ nm}$, $b = 0.356 \text{ nm}$ and $c = 0.437 \text{ nm}$. From xy axis, V-O layer-like structure with two oxygen in z axis

| Phase | Lattice | Space group |
|--------------------------------|--------------|-------------|
| VO | Cubic | Fm3m |
| VO ₂ | tetragonal | P42/mnm |
| | tetragonal | I4/mmm |
| | tetragonal | I41/a |
| | orthorhombic | Pmnn |
| | orthorhombic | Pmcn |
| | orthorhombic | Pnmb |
| | monoclinic | C2/m |
| | cubic | Fd3m |
| | trigonal | R3m |
| Magnéli | | |
| V ₆ O ₁₃ | monoclinic | Cm |
| | monoclinic | C2/m |
| | orthorhombic | Fmmm |
| V ₃ O ₇ | monoclinic | C2/c |
| V ₂ O ₅ | orthorhombic | Pmnm |
| | orthorhombic | Pmnb |
| | orthorhombic | Pmna |
| | orthorhombic | Cmcm |
| | monoclinic | P21/m |
| | monoclinic | C2/m |
| | monoclinic | C2/c |
| | triclinic | P1 |
| Wadsley | | |
| V ₃ O ₅ | monoclinic | P2/c |
| | monoclinic | C2/c |
| V ₄ O ₇ | Triclinic | P1 |
| V ₅ O ₉ | Triclinic | P1 |
| V ₆ O ₁₁ | Triclinic | P1 |
| V ₇ O ₁₃ | Triclinic | P1 |
| V ₈ O ₁₅ | Triclinic | P1 |

Table 1.
Examples of phases and structures of V-O phase diagram.

forming a distorted trigonal bipyramidal coordination polyhedral. Each combination of VO₅ pyramids has planes (00 l) and V is linked with five oxygen atoms by single bonds being four oxygen in xy axis and one oxygen in z axis. Then, in series of planes of VO₅ are connected with alternating oxygen position in z axis (perpendicular) according to the sequence two up and two down. Therefore, the V-O single bond in perpendicular position presents a weak interaction compared to oxygen located in adjacent layer [7, 11]. This layered characteristic makes enable an introduction of several ions into the lamellar spacing which bringing change of the crystalline structure resulting in different properties (**Figure 1**).

V-O bonds from V₂O₅ have different distance caused by spontaneous deformation of the geometry to reduce the energy of the system. Then, vanadyl bond with four oxygen from the plane present a value of 0.178 nm. The bond of the extension along the z axis has 0.279 nm and the vertical axis opposite to the V–O bond has 0.158 nm.

Depending on the conditions, vanadium oxidation states might range of V²⁺ to V⁵⁺ as well as changes in coordination geometrics. Structural evolution in function of pH and concentration of V₂O₅ precursors are responsible by different oxidation

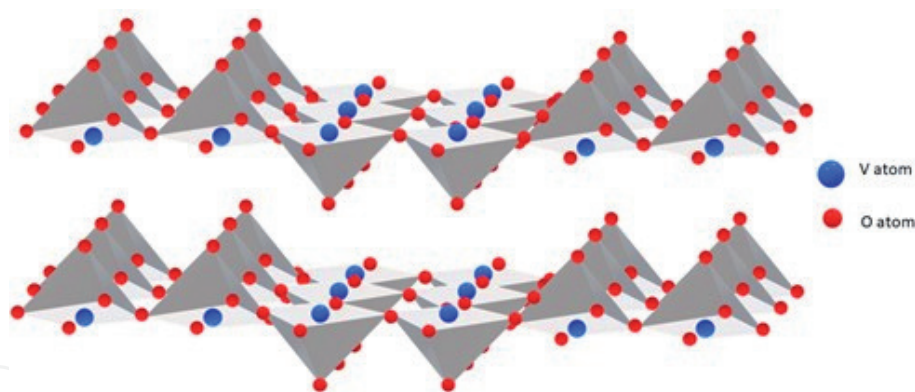


Figure 1.
Perspective view of two layers of V_2O_5 . Weak van der Waals bonds are omitted for clarity.

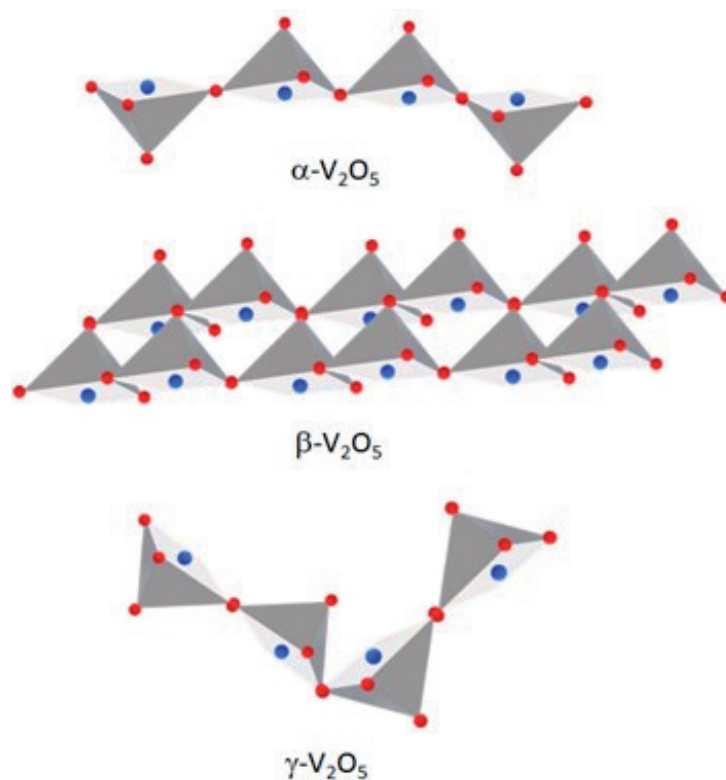


Figure 2.
Structures polymorphs of V_2O_5 .

states. Whenever a decrease of pH (13 to 1) and increase of H^+/V (1 to 3 and concentration range from 10^{-3} to 10^{-1} mol.L $^{-1}$) there are predominant species such as pyrovanadate, metavanadates, decavanadates, respectively. The main reaction that occurs during the formation of V_2O_5 are called ololation and oxolation which will be detailed in Section 3.

It is possible to find V_2O_5 as α , β , and γ polymorphs (**Figure 2**) and among them have four orthorhombic, two monoclinic and one triclinic phase. α - V_2O_5 is a stable phase with an interlayer spacing of 0.452 nm. After a distortion forming by VO_6 in the V_2O_5 structure, V atoms are dislocated to the corner from the middle forming β - V_2O_5 . γ - V_2O_5 presents oxygen alternated up and down pyramids connected with vanadium in the center and each VO_5 square pyramids forming zig-zag structure. There is a $V=O$ bond along z axis that presents a weak bond and a covalent bond along x and y axis, creating double layers of O-V-O which is considered as short and strong. These torsion on structure makes γ - V_2O_5 more flexible and results in a structure metastable [12, 13].

The double layers of O-V-O are separated by van der Waals bond being a weak one. The different bonds along the coordinates of V_2O_5 creating a strong anisotropic in the V_2O_5 as 2-D layered material. Then, the basal plane (010) presents lower surface energy compared to (100) and (001) planes. As V_2O_5 presents plane as stacking of playing cards with weak interlayer force, it is possible to provides an intercalation reaction with several substances [12].

3. Structure of V_2O_5 based on its obtaining methods

In this section various conditions of synthesis and preparation methodology will be approached as well as their structural influences on V_2O_5 . The interesting of V_2O_5 is focused on its versatility in several applications based on obtaining methods. The most used preparation technique is sol-gel but other methods such as hydrothermal/solvothermal synthesis, electrospinning, chemical vapor deposition (CVD), physical vapor deposition (PVD), template-based methods, reverse micelle techniques, Pechini method and electrochemical deposition can be used as well. Often, combinations of these methods can be found to obtain different structures of V_2O_5 . The control of reaction conditions allows the formations of V_2O_5 as powder, nanomaterial, thin films, porous materials, among others.

Sol-gel – The sol-gel method (or synthesis or process) is basically based on hydrolysis and condensation of precursor material. This method was reported by Ditte in 1885 [14] that observed a formation of a red sol when the ammonium vanadate precursor was heated with nitric acid and water inside of platinum crucible. Other similar experiments were published some years later by Blitz [14]. During the sol-gel process the formation of V_2O_5 occurs during the olation and oxolation stages in pH 2 (**Figure 3**). Throughout the olation, the V^{5+} central is hexacoordinate with water and, opposite side, oxygen with double bond in z axis. Other four bonds are orientated in the equatorial plane which x axis occur water and -OH bonds in opposite sides. Finally, in y axis there are two bonding of -OH in opposite sides. Due to distortion in the structure the length of bonds is not equal and the release of water molecule from x axis occurs resulting in the connection between V^{5+} central link with oxygen from the other molecule coordinate forming the olation chain polymers. After the olation occurs a reaction in z axis called oxolation. The oxolation lead to the formation of edge sharing double chains in y axis. During this stage occurs a condensation resulting in polymerization of $(-O-V-O')_n$, which linked together whit O' from other $-O'-V-$ molecule coordinate. Finally, orderly planes along the y axis of polymerized VO_x are formed and connected by Van der Waals force. Other planes are generating a lamellar structure with interlayer distance around 1.17 nm [15]. Through this interlayer spacing, it is possible to perform an intercalation reaction of different substances without interfering in the crystallinity of V_2O_5 (topotactic process) [15–18]. Intercalation reactions yield new materials with different or improved properties (synergic effect). V_2O_5 obtained from sol-gel synthesis has low viscosity, reddish brown color and after dry in room temperature is formed a xerogel of V_2O_5 thin film. The properties will be discussed in Section 4.

Hydrothermal/solvothermal synthesis – Hydrothermal and solvothermal synthesis or method is widely used in inorganic synthesis. This method is often carried out in an autoclave with high-temperature aqueous solutions at high vapor pressures. Then, hydrothermal method can be defined as a method of synthesis of crystals or particles that depends on the solubility of inorganic material in hot solution under high pressure. V_2O_5 obtained from hydrothermal synthesis is a powder solid and generally use a salt of metavanadate. The V_2O_5 power presents an orthorhombic oxide α - V_2O_5 that exhibits a layered structure made of edge and corner sharing

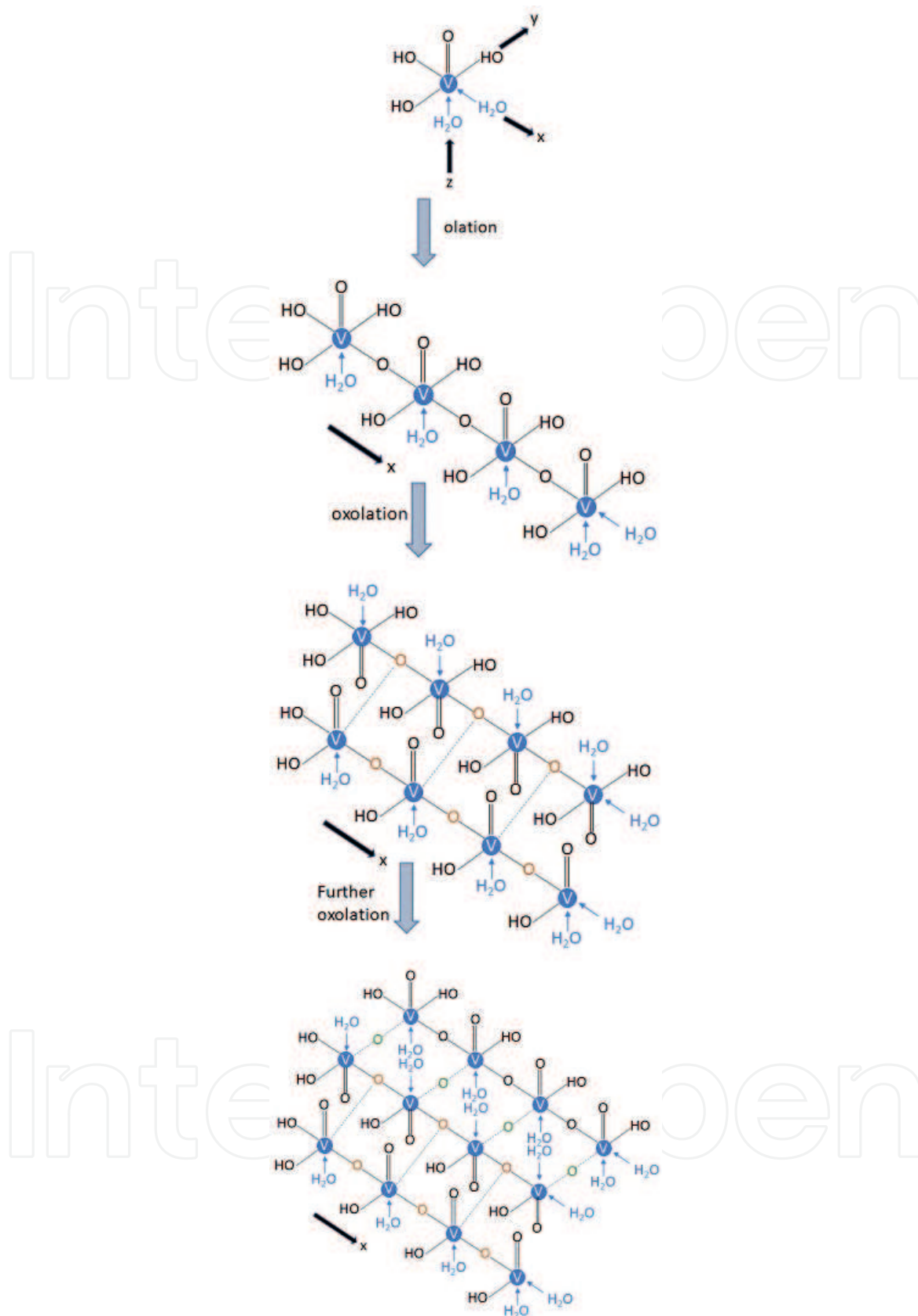


Figure 3.
The formation of V_2O_5 .

$[VO_5]$ double chains [19]. However, there are several vanadium coordination as trigonal bipyramids to square pyramids and tetrahedra as well as a variety of crystalline V_2O_5 . Additionally, varying conditions it is possible to obtain different nanostructure from hydrothermal synthesis as nanowires, nanobelts, nanorods, nanotubes, nano-urchin shapes, hollow nanospheres, nanosheets and nanoflowers.

Porous material as micro, meso and macroporous can be obtained as well. The combination of hydrothermal synthesis with V_2O_5 obtained by sol-gel route can generate new materials with different structures and scale.

Electrospinning – electrospinning is a method that presents low cost, easy to control, simple and versatile. The method was patented by J.F. Cooley in February 1902 (U.S. Patent 692,631) and by W.J. Morton in July of the same year (U.S. Patent 0,705,691). This method consists of a syringe needle connected to a high voltage power supply (5 to 50 kV), a syringe pump and a collector. Voltage is applied and the sol-gel is ejected from needle tubing forming a nanowire. Thus, voltages, viscosity of the sol-gel, speed of syringe pump, and the humidity are the key factors which will affect the nanostructure of the nanowire. The solution is ejected from the needle tip with a constant rate by a syringe pump with constant feed pressure. Then, the high voltage applied transforms the liquid charged and the electrostatic repulsion counteracts the surface tension, and the droplet is stretched. Through the electrostatic repulsion, small bends in the fiber are deposited on the grounded collector. Due to the manner of deposition, the elongation and thinning of the fiber leads to the formation of uniform fibers with nanometer-scale diameters with novel physical properties [20]. With controlled deposition, the improve of properties is achieved and which leads to an enhancement of surface being the key to properties for superior chemical sensors.

Chemical vapor deposition (CVD) – chemical vapor deposition presents a film control composition via the control of chemical precursors producing a nanostructure V_2O_5 thin film. It is an interesting method because material is produced by the chemical reaction of vapor phase precursors in the gas phase and at the substrate surface. CVD presents advantage as precise control of film composition and it can coat large areas. There are variant of chemical vapor deposition (CVD) methods: thermally activated CVD (TACVD), plasma-enhanced CVD (PECVD), photo-initiated CVD (PICVD), pulsed-pressure metal organic CVD, atmospheric pressure CVD, atomic layer deposition, spray pyrolysis, plasma-enhanced CVD, aerosol-assisted CVD and so on [21, 22]. Basically, a vanadium precursor is dissolved in a solution and transported using ultrasonic. Then, the solution is put into a heated reactor with N_2 carrier gas. When the reaction is completed, about 1 h, the reactor is cooled to room temperature. The as-deposited coatings were brightly yellow in color and strongly adhered to the substrate [23]. The material obtained is transported to the substrate surface in the form of vapors, gases and volatilized liquid or in some cases a solid, would sublime directly and is generally prepared by injection of the liquid into solvent or heated evaporators [21, 22].

Template-based methods – this method for synthesis of nanostructured materials using templates is been widely used [24]. It consists of the use of molders with desired morphology as a template to guide the formation of products, which as, a result possess a similar morphology with the template after calcination. The template presents different shapes that can be controlled through adjusting parameters. Guerra *et al.* [25] investigate the effect of the mesoporosity exhibited by a meso-structured vanadium oxide obtained by sol-gel process and used as host cathode matrix on the Li^+ insertion/deinsertion process. Basically, all the proposed mechanisms are based on the same principle: the molecules of the surfactant (or structural directive) play a central role in molding or template for the formation of the mesoporous material. From the general point of view, the mechanism of formation of the mesoporous phase is based on electrostatic interactions between an inorganic precursor (I) and a surfactant (S) through a cooperative mechanism. The reaction involves a cationic surfactant and a negatively charged inorganic species, called S^+I^- synthesis. Similarly, this same group proposed syntheses using S^-I^+ , $S^+X^-I^+$ (where X is a counterion) and $S^-M^+I^-$ (where M is a metallic cation). In the case of neutral

S and I, it is believed that the process of self-organization takes place by hydrogen bonds. Through the use of templates, such as self-assembled organic surfactant, it is possible to obtain nanomaterials of different oxides [17, 24]. Nevertheless, this method presents disadvantage because the template used during the process needs to be removed by calcination, for example, at the end of synthesis increasing the cost and makes the preparation more complex.

Reverse micelle techniques (RM)– RM is used to prepare V_2O_5 nanostructured. To obtain nanomaterials are used nanometer-sized aggregates of surfactants with encapsulated water molecules inner the solvent. Different surfactants, including anionic, cationic, zwitterionic, nonionic and mixed surfactants can be used [26]. The nanometer-sized can be controlled by the water content expressed by (mol [water]/mol [surfactant]). Sulphosuccinic acid bis (2-ethylhexyl) ester sodium salt (AOT) is an anionic surfactant that is widely used to prepare RM to obtain V_2O_5 nanorods [27]. Pinna *et al.* [27] prepared V_2O_5 nanostructured from AOT with ([H₂O]/[AOT]) being 10. From high-resolution images and structural characterization, it was possible to observe a lattice fringes of the nanocrystals with the γ - V_2O_5 structure for the nanorod oriented in the [101] direction and for the nanowire oriented in the [100] direction.

Electrochemical deposition - Electrochemical deposition or electrodeposition is frequently used to prepare nanomaterials or porous materials. This method has many advantages as low costs and flexibility compared to other methods. Besides, during the electrodeposition is possible to use room temperature and pressure. A nanomaterial can be synthesized using a small amount of templating agent to assemble and an electrochemical potential applied. The size of porous can be controlled by varying the electrodeposition conditions, such as deposition voltage, deposition time and surfactant concentration. After electrodeposition, the templating agent can be removed easily by washing with an appropriate solvent or calcination [28]. Generally, to prepare V_2O_5 by electrodeposition is used $VOSO_4$ as precursor in a mixture of deionized water and ethanol. A counter electrode and Ag/AgCl reference electrode are used during the electric voltage applied and the electrodeposition occurs onto an ITO/glass electrode. The pH can be adjusted according to the material to be obtained [29].

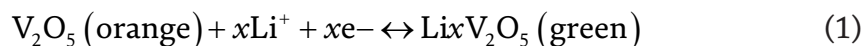
Pechini method – Pechini method is a kind of sol–gel method and is well-known wet chemical technique. During the synthesis is possible to use the same precursor of sol–gel method cited previously, but Pechini method involves the addition of alcohol and citric acid at room temperature resulting in a solid polymeric. The advantage of this method is ensuring compositional homogeneity of surface, low cost, homogeneous mixing at the molecular or atomic level, stoichiometric control, a lower calcining temperature, and a shorter heating time [30]. Then, from this method is possible to obtain V_2O_5 polycrystals with lattice parameters: $a = 1.1514$ nm, $b = 0.3565$ nm, $c = 0.4374$ nm, $\alpha = \beta = \gamma = 90^\circ$ and lamellar morphology [31].

4. Properties and applications

V_2O_5 is a versatile material in terms of properties and importance in technological applications. This versatility is designed by rich morphologies and structures, various synthetic methods giving excellent properties. It is good to highlight that commercial V_2O_5 does not present electrochromic properties, for example, because of its low electrical conductivity, poor coloration efficiency and narrow color variation. Then, since the first synthesis of V_2O_5 several many studies have been proposed with the objective of obtaining this same oxide, however, with different

syntheses. Thus, it was found that the change in preparation to obtain V₂O₅ had several important characteristics that result in structural change and, consequently, in the final properties and applications. Among them, it is observed that each type of synthesis causes variation in the band gap resulting in the variation of semi-conductivity of V₂O₅. Generally, from the Tauc plot is possible to obtain the band gap value of V₂O₅. The value of the V₂O₅ band gap may shift, but always within the range of semiconductive materials. This result directly impacts in many final properties of this material. Then, with the innumerable possibilities of synthesis for obtaining V₂O₅ it became possible to make a structural and morphological manipulation resulting in a wide and varied potential in applications. Studies using V₂O₅ are mainly focused on characteristics and properties such as, electronic, magnetic, conductive, electrochemical, optical, mechanical, catalytic chemisorption among others.

More specifically, V₂O₅ can exhibit wide interesting and useful properties including metal-insulator transitions and electron. As addressed above, a layered structure like orthorhombic α -V₂O₅ can be a host for cation intercalation and potential application in Li-ion batteries. However, other metastable polymorph ζ -V₂O₅ is found to open up the possibility of controlling the charge ordering of the network, and makes a prime candidate for applications in the next generation of Li- and multivalent-ion cathode materials [32]. The insertion/deinsertion of Li⁺ occurs according to the reaction (1):



There are other phases that occur as lithiated vanadium oxide Li_xV₂O₅ during the redox reaction. The amount of lithium, x , presents a variation according to the structure: α -V₂O₅ ($x < 0.01$), ϵ -Li_xV₂O₅ ($0.35 < x < 0.7$), δ -Li_xV₂O₅ ($x = 1$), γ -Li_xV₂O₅ ($x < 2$) and ν -Li_xV₂O₅ ($x > 2$) [7]. Structure manipulation to remodel V₂O₅ as nanosheet-assembled hollow microflowers by solvothermal method exhibits high specific capacity and remarkable cycling stability due to hierarchical structure with nanosheet subunits and hollow interior [10]. Regarding to electro-deposition of V₂O₅, this nanostructured material obtained can present high energy density, power density, good cyclic stability over 200 cycles as high power and energy densities for thin film Li-ion batteries [33] and it has 5 times higher current density than sol-gel-derived film and can intercalate up to 5 times higher concentration of Li⁺ [29]. Nanostructures can promote a rapid and facilitate the electron transfer ensuring satisfactory capacity retention even at high current densities, reduced ion diffusion distance and improved surface area. In theoretical terms, the specific capacity is much greater than those commercialized [8]. In general, using electrochemical studies to application as supercapacitor, V₂O₅ presents high capacitance and great energy density. A supercapacitor is an energy storage component, and comparing with battery, a supercapacitor presents more long lifetime, high power density, eco-friendly material and high efficiency [34]. It was found that V₂O₅ presents a range of 140 to 704.17 F.g⁻¹ [34] using different synthesis and, consequently, different structures. It was found that the stability was 94.3% after 10,000 cycles indicating the potential of the V₂O₅ electrode for supercapacitor [35]. In general, V₂O₅ compound presents advantages in energy storage devices as ease to prepare even different method of synthesis, wide lithiation/delithiation potential and abundant storage.

V₂O₅ can be used as counter electrode (CE) in dye-sensitized solar cells (DSSC). Different methods to prepare V₂O₅ was demonstrated in literature [36–38]. The presence of V₂O₅ as component in DSSC contributed with power conversion

efficiency in range of 2.04 to 3.80% using different method of obtaining as well as exhibited longer lifetime in an ambient environment, ease of film preparation at room temperature, low production cost and high optical transmittance over a wide range of solar spectrum [36, 37].

A gas sensor has a possibility to detect several gases in different atmospheres transforming the chemical reactions to analytically useful detectable signals. Then, the efficiency of a gas sensor depends on the materials present in sensor and the interaction of the gas with the material. The temperature can be an important factor between interaction of gas with materials on the surface of the sensor. Therefore, the choose of the material is particularly important. Consequently, V_2O_5 is found in several studies being a sensing material for several gas, such as, ammonia, ethanol, pH-sensor, EGFET pH-sensor, phenylhydrazine, NO_2 , H_2O_2 and among others. In all cases, V_2O_5 demonstrated to be highly sensitivity in several temperature and under both dark and illumination conditions [18, 39–47]. Similar to the sensor, a biosensor turn an analytical response into a measurable chemical signal and detects only a certain biological product as a target analyte. The use of different structures of V_2O_5 as sensitive component in biosensor device has been explored in several target analyte such as urea, glucose, gene sequence, EGFET-biosensor, methylglyoxal in rice and among others [48–53].

V_2O_5 presents optical property upon charging/discharging resulting in the color change. This ability to change its color by redox reaction is denominated electrochromic effect [54]. During the charge insertion into the vanadium is observed that the transmittance increases in the ultraviolet in a short wavelength of the spectrum, while the transmittance drops in the long-wavelength part of this spectrum near in infrared region. The optical and multicolor characteristics in V_2O_5 generate several applications such as in transmittance smart windows in energy efficient buildings, displays, in reflectance mirrors and emittance surfaces for temperature control of space vehicles. During the Li^+ extraction from V_2O_5 in range potential from -0.6 to $+0.6$ V the color of the film changes the deep blue to green and, finally, to yellow due to the oxidation of V^{4+} to V^{5+} . Initially, only partial V^{4+} ions change to V^{5+} at -0.3 V. In region more positive of potential, the remaining V^{4+} ions turn to V^{5+} . The reduction reaction occurs when the shift of potential to region more negative is applied makes the V_2O_5 a reversible capacity after several cycling [11, 55].

5. Conclusion

V_2O_5 has traditionally been used in various applications based on its obtained methods and properties of final structure. This chapter has summarized these obtaining methods using vanadium pentoxide with emphasis in different structure for wide applications. Since the first publication of V_2O_5 using sol-gel method, many reports have been found. The versatility and stability of V_2O_5 generated studies about structural changes according to the property of interest. Then, based on different obtaining techniques, it was possible to find structures of V_2O_5 such as nanostructures, lamellar, among others. Therefore, growth techniques have contributed to the extensive range of V_2O_5 applications. Additionally, depending on the conditions and methods, V_2O_5 films can have considerably different structural, optical, conductivity and electrical properties. The characteristic of V_2O_5 in offers a wide possibility of synthesis, low cost, easy to be obtained, reveals that the material has high potential in several application areas being technological or innovation. Besides, in all application, the use of V_2O_5 has been demonstrated a promisor response and in a near future, the technology of designing new devices will have, as one of the components, the V_2O_5 presents on scale range.

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Conflict of interest


The authors declare no conflict of interest.

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