



Review Paper

## Vanadium Pentoxide Cathode Material for Fabrication of All Solid State Lithium-Ion Batteries - A Case Study

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### Abstract

Transition metal oxides have been a subject of research in recent years in view of their fundamental and technological aspects. Among these, vanadium creates many compounds with oxygen; these have different structural, optical and chemical properties. Vanadium pentoxide ( $V_2O_5$ ) is a thermodynamically stable form which exhibits electrochromic properties. A lot of recent research has been focused on the synthesis and fabrication of nanostructured vanadium oxides to mitigate the slow electrochemical kinetics with high specific surface area and short diffusion distance. Vanadium pentoxide with a layered structure is promising for smart window applications.  $V_2O_5$  crystallizes with an orthorhombic unit cell and belongs to  $P_{mmm}$  space group with lattice parameter  $a = 11.510 \text{ \AA}$ ,  $b = 3.563 \text{ \AA}$ ,  $c = 4.369 \text{ \AA}$ , where the  $b$  and  $c$  are often interchanged. The stoichiometry of  $V_2O_5$  is considered as deformed octahedral  $VO_6$  which serves as the building block of the  $V_2O_5$  structure. As a thin film, it exhibits multi colored electrochromism and has high potential for use in electrochromic display devices, color filters and other optical devices. Bulk and thin film  $V_2O_5$  with vanadyl oxygen vacancies have been used as an oxidation catalyst. This paper deals with the detailed technological aspects of properties, different structures of  $V_2O_5$  as candidate cathode material for the fabrication of all solid state lithium ion batteries with wide applications of  $V_2O_5$  films as electrochromic cells and gas sensors.

**Keywords:**  $V_2O_5$  cathode material, layered structure, properties,  $V_2O_5$  nanostructures,  $V_2O_5$  films, applications, electrochromic cells and gasochromism.

### Introduction

The basis of all materials science involves relating the desired properties and relative performance of a material in a certain application to the structure of the atoms and phases in that material through characterization. The major determinants of the structure of a material and thus of its properties are its constituent chemical elements and the way in which it has been processed into its final form. In addition to industrial interest, materials science has gradually developed into a field which provides tests for condensed matter or solid state theories. Therefore studying about materials science can be a bridge to a career in any of these emerging technologies. Among the materials that meet the current prerequisites, metal oxides with many interesting physical and chemical properties have been scientifically and technologically exploited in many fields like environmental science, electrochemistry, microelectronics, optoelectronics and relating fields. Depending upon their physical properties, they can be broadly categorized into the significant groups such as non-transition metal oxides and transition metal oxides.

Transition metal oxides have been a subject of research in recent years in view of their fundamental and technological aspects. Among these, vanadium creates many compounds with oxygen;

these have different structural, optical and chemical properties. Meaningful differences between the properties of different phases of vanadium oxides like VO,  $VO_2$ ,  $V_2O_3$  and  $V_2O_5$  depend on their structure, which determines other properties. Different forms of vanadium oxides can be obtained by changing the deposition process parameters, or by post-process treatment, e.g., additional annealing. From the application point of view, the most interesting vanadium oxides are  $VO_2$  and  $V_2O_5$ . Vanadium dioxide is a very good candidate for thermochromic coatings due to the change of properties from semiconducting to semimetal at 68 °C. Vanadium pentoxide is a thermodynamically stable form which exhibits electrochromic properties.  $V_2O_5$  thin films can also be used in optical filters, reflectance mirrors, smart windows and surfaces with tunable emittance for temperature control of space vehicles.

In the past decade, nanostructured vanadium oxide compounds have attracted much interest due to their chemical and physical properties and their great potential for applications in catalysis<sup>1</sup> as sensors in electrochromic devices in electrochemistry in photocatalytic activities and in spintronic devices. Among the various vanadium oxide compositions that can be obtained, vanadium pentoxide possesses a unique set of properties and is one of the most widely studied of the more stable phases of vanadium oxides<sup>2</sup>. Because its structure is composed of two-

dimensional layers, this material is also used as an intercalation compound. Since the reversible electrochemical lithium ion intercalation in  $V_2O_5$  was first reported in 1976 vanadium pentoxide has been intensively investigated as a cathode material for rechargeable lithium-ion batteries because of its low cost, abundance, easy synthesis, and high energy density<sup>3</sup>. It is a typical intercalation compound with a layered crystal structure, with a large variety of atomic and molecular species that can be reversibly intercalated and extracted between the layers. However, the development of rechargeable lithium-ion batteries with vanadium pentoxide as a cathode has been limited for its poor structural stability, low electronic conductivity and ionic conductivity and slow electrochemical kinetics.

When  $V_2O_5$  intercalates  $Li^+$ , electrical energy stores in the electrode. Energy releases from the electrode when  $Li^+$  diffuses out. For electrochemical pseudo capacitor applications, the charge/discharge rate and the energy storage capacity are the most important parameters. Larger surface area and easy charge transport are required to achieve high charge/discharge rate<sup>4</sup>.  $V_2O_5$  xerogel and aero gel, both offer large surface area, have been explored for such application and have demonstrated a current density of 6 C (C is about 150 mAh/g  $V_2O_5$ ) without storage loss. However,  $V_2O_5$  xerogel and aerogels are well-known to suffer from their structural stability; the porous structure readily collapses during  $Li^+$  intercalation and extraction processes.

$V_2O_5$ , as an active lithium ion intercalation host, has been intensively studied as the positive electrode material for lithium ion batteries for the past decades and has recently been commercialized;  $V_2O_5$  electrodes fabricated by various methods like sputtering thermal evaporation, electrophoretic deposition<sup>5</sup> and sol-gel casting were all studied for their lithium ion intercalation capabilities. Chemical composition, crystal structure and crystallinity, and micro- and nanostructures were all found to play critical roles in determining lithium ion intercalation capacities and cyclic stabilities. However, even with optimized micro, and nanostructures and crystallinity, the practical application of vanadium oxides in lithium ion batteries was still limited by the relatively poor cyclic stability though this is a general concern for most lithium ion intercalation electrodes and researchers have been actively searching for effective methods to solve this problem. Surface coating has shown to be a viable method to improve the intercalation cyclic stability. For example, a thin layer of carbon or inert oxides could prevent the active material (electrode) from dissolution in the electrolyte while at the same time improving the electrode/electrolyte interfacial charge transfer process. This surface coating has already been successfully used on commercialized cathode materials, such as  $LiCoO_2$  with well improved cyclic stability<sup>6</sup>.

A lot of recent research has been focused on the synthesis and fabrication of nanostructured vanadium oxides to mitigate the slow electrochemical kinetics with high specific surface area

and short diffusion distance. For example, single-crystal  $V_2O_5$  nanorod arrays demonstrated much improved electrochemical Li-ion intercalation properties<sup>7</sup>. Such improvement has been attributed to the long axis (growth direction) of the single-crystal nanorod arrays parallel to the interlayer of  $V_2O_5$ , and thus providing shorter and simpler diffusion paths for lithium ions and allowing the most freedom for dimension change accompanying the lithium ion intercalation and extraction. Similar enhancement has been found in platelet and febrile structured  $V_2O_5$  films; however, some nanostructured films suffer from poor cyclic stability. The cyclic stability could be improved when nanostructures are appropriately designed and fabricated<sup>8</sup>. Doping transition metal ions has been studied for improved lithium ion intercalation properties. For example, doping of Ag and Cu in vanadium oxides<sup>9</sup> has been reported to result in much improved electrochemical properties of  $V_2O_5$ .

Electrochromic materials are those which exhibit a reversible optical change between the transparent state and the colored state upon charging or discharging via electrochemical reactions. Variable transmittance windows (smart windows), display devices, and controlled reflectance mirrors for vehicles are typical applications of this property, and the smart window is currently one of the most dynamic research areas. Vanadium pentoxide with a layered structure is promising for smart window applications. However, the diffusion coefficient of Li ions in  $V_2O_5$  ( $10^{-12}$ – $10^{-13}$   $cm^2/s$ ) and the electrical conductivity of  $V_2O_5$  ( $10^{-2}$ – $10^{-3}$  S/cm)<sup>10</sup> are both small and, thus the intercalation process is relatively slow. A large surface area and a short diffusion distance are desired to achieve faster intercalation and extraction kinetics. One effective way to achieve these properties is the use of one-dimensional nanostructures, such as nanowires, nanorods and nanotubes. Although various methods have been developed for the formation of nanorods or nanowires template-based synthesis is one of the most attractive fabrication methods as this approach provides unidirectionally aligned uniformly sized nanorod arrays<sup>11</sup>.

## Importance of Vanadium Pentoxide

Vanadium oxides are the class of transition metal oxides with vanadium oxidation states ranging between +2 to +5 in general. These oxide materials have most fascinating technological applications and academic interest. Vanadium oxides show different properties with various compositions. Electrical, Optical and Chemical properties of vanadium oxides are different from other transition metal oxides and have significant applications in various fields. It is a low mobility semiconductor with predominantly n-type conductivity. Vanadium oxide in the form of thin film at small thickness show enhanced properties as follows. Vanadium pentoxide is a good cathodic material and it hosts Li ions in its tetrahedral sites and it is quite suitable for insertion and deinsertion of Li ions. On intercalation mechanism of cations i.e inserting and deinserting the cations it changes its color which is referred as electrochromism. When these oxides

are subjected to temperature which involves strong variations in optical transmittance, reflectance and emissivity. Upon exposure to several organic gases these oxides change their color which is known as gasochromism, making possibility for sensing hydrogen in organic gases. Vanadium pentoxide is a good catalyst in several chemical reactions. For example in contact process for sulfuric acid preparation  $V_2O_5$  used as catalyst and also I thin film form it enhances the oxygenated dehydrogenation (ODH) reactions. These oxides are also capable of oxygen and pH sensing and IR detection. These vanadium oxides show both p-type and n-type conductivity depending on substrate and temperature.

### Structure of Vanadium Pentoxide

Vanadium oxide, in general may refer to following main four types of oxides with +2, +3, +4 and +5 oxidation states respectively. i. Vanadium (II) oxide (vanadium monoxide),  $VO$ , ii. Vanadium (III) oxide (vanadium sesquioxide or trioxide),  $V_2O_3$ , iii. Vanadium (IV) oxide (vanadium dioxide),  $VO_2$ , iv. Vanadium (V) oxide (vanadium pentoxide),  $V_2O_5$

In addition to these principal oxides of vanadium, various other distinct phases also exist as follows: i. Phases with the general formula  $V_nO_{2n+1}$  where  $n = 2, 4, 6$  exist between  $V_2O_5$  and  $VO_2$ . Examples of these phases include  $V_3O_7$ ,  $V_4O_9$  and  $V_6O_{13}$ . ii. Phases with the general formula  $V_nO_{2n-1}$  where  $2 \leq n \leq 8$  exist between  $VO_2$  and  $V_2O_3$  and are called Magneli phases, they are examples of crystallographic shear compounds based on the rutile structure. Examples of Magneli phases include  $V_4O_7$ ,  $V_5O_9$ ,  $V_6O_{11}$ ,  $V_7O_{13}$  and  $V_8O_{15}$ . iii. Other possible phase is  $V_nO_{2n}$  where  $n = 2$  only.

Among the family of the vanadium oxides, vanadium pentoxide is the most stable compound with highest oxygen concentration and it can be built from corner-sharing and edge-sharing  $VO_6$  octahedra.  $V_2O_5$  crystallizes with an orthorhombic unit cell and belongs to  $P_{mm}$  space group with lattice parameter  $a = 11.510 \text{ \AA}$ ,  $b = 3.563 \text{ \AA}$ ,  $c = 4.369 \text{ \AA}$ , where the  $b$  and  $c$  are often interchanged. The stoichiometry of  $V_2O_5$  is considered as deformed octahedral  $VO_6$  which serves as the building block of the  $V_2O_5$  structure. The octahedra are irregular in  $V_2O_5$  with five V-O distances between  $1.585$  and  $2.021 \text{ \AA}$  and a sixth distance as large as  $2.79 \text{ \AA}$ . The deformed  $VO_6$  octahedra form wrapped layers in which oxide anions are shared by adjacent octahedra. From this structure it is assumed that only weak van der Waals type interaction exist between the layers. Thus the crystal structure of  $V_2O_5$  is a layered structure (the layers are  $4.4 \text{ \AA}$  apart) with easy cleavage along (001) plane.

The molecular structures of surface vanadia species have been extensively investigated in the past few years with many different spectroscopic methods: Raman, IR, XANES /EXAFS, solid state  $51V$  NMR, UV-VIS DRS, chemi-luminescence, and ESR<sup>12</sup>. The local structure of  $V_2O_5$  supported on silica and alumina has been most intensively studied. In general, ESR and

UV/VIS results are consistent with each other, although ESR results are restricted to paramagnetic  $V^{4+}$  containing species. On silica, vanadium atoms are generally stabilized in an oxygen tetrahedron in the dehydrated state. Hydrated silica supported  $V_2O_5$  mostly exists in an octahedral configuration. On alumina, both ESR and UV/VIS studies demonstrated that vanadium is five- or six-fold co-ordinated by oxygen. However, Raman studies revealed the formation of different types of vanadium oxide species: polymeric arrays of octahedral  $VO_6$  units as the main phase and tetrahedral  $VO_4$  species as a minor constituent on both, silica and alumina. Figure -1 shows Layered structure of vanadium pentoxide<sup>13</sup>.

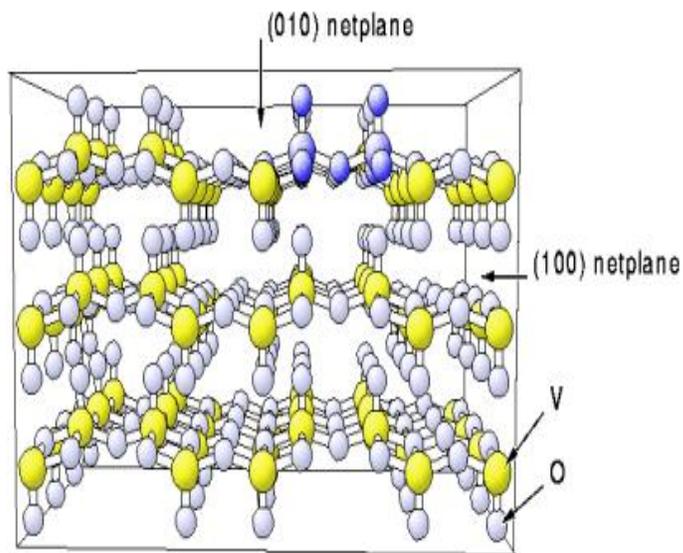


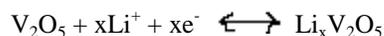
Figure-1  
Layered structure of Vanadium Pentoxide

### Properties of Vanadium Pentoxide

Vanadium pentoxide is an odorless, yellow-red, crystalline solid slightly soluble in water and soluble in acid. Its melting point is 1274 degrees Fahrenheit, or 690 degrees Celsius. At 3182 degrees Fahrenheit or 1750 degrees Celsius, vanadium pentoxide decomposes into other vanadium oxide compounds. The specific gravity of the compound is 3.36. As the source material for vanadium and the compound ferrovanadium, vanadium pentoxide finds use in the steel industry, chemical manufacturing and ceramics. Vanadium pentoxide warrants special attention due to the toxicity of its fumes and dust particles. Inhalation or ingestion of vanadium pentoxide can be fatal and OSHA has established a ceiling exposure limit of 0.5 milligrams of vanadium pentoxide dust per cubic meter of air and a ceiling exposure limit of 0.1 milligram of vanadium pentoxide fume per cubic meter of air. The National Institute for Occupational Safety and Health, or NIOSH, recommends 0.05 milligrams per cubic meter of air as a 15 minute ceiling for exposure to vanadium pentoxide dust or fume. A well-ventilated work area or fume hood, protective clothing and eye protection are needed whenever working with vanadium pentoxide and

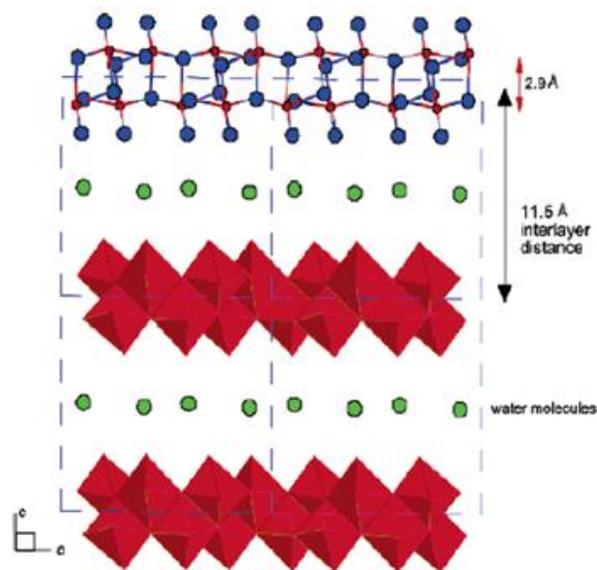
respirators should be used when exposure limits cannot be effectively controlled.

Vanadium pentoxide is a typical intercalation compound as a result of its layered structure. Intercalation compounds are a special family of materials. The intercalation refers to the reversible intercalation of mobile guest species (atoms, molecules, or ions) into a crystalline host lattice that contains an interconnected system of an empty lattice site of appropriate size, while the structural integrity of the host lattice is formally conserved. The intercalation reactions typically occur around room temperature<sup>14</sup>. A variety of host lattice structures have been found to undergo such low-temperature reactions. However, the intercalation reactions involving layered host lattices have been most extensively studied, partly because of the structural flexibility and the ability to adapt to the geometry of the intercalated guest species by free adjustment of the interlayer separation. The readers are referred to a comprehensive and excellent article on inorganic intercalation compounds. Despite the differences in chemical composition and lattice structure of the host sheets, all the layer hosts are characterized by strong interlayer covalent bonding and weak interlayer intercalations. The weak interlayer intercalations include vanderWaals force or electrostatic attraction through oppositely charged species between two layers. Various host lattices are metal dichalcogenides, metal oxyhalides, metal phosphorus trisulfides, metal oxides, metal phosphates, hydrogen phosphates, phosphonates, and graphite and layered clay minerals. Guest materials include metal ions, organic molecules, and organometallic molecules. When guest species are incorporated into host lattices, various structural changes will take place. The principle geometrical transitions of layered host lattice matrixes upon intercalation of guest species include i. change in interlayer spacing, ii. change in stacking mode of the layers, and iii. formation of intermediate phases at low guest concentrations that may exhibit staging. There are various synthesis methods for the formation of intercalation compounds<sup>15</sup>. The most commonly used and simplest method is the direct reaction of the guest species with the host lattice. For direction reactions, the intercalation reagents must be good reducing agents of the host crystals. Ion exchange is a method to replace the guest ion in an intercalation compound with another guest ion, which offers a useful route for intercalating large ions that do not directly intercalate. Appropriate chosen solvents or electrolytes may assist the ion exchange reactions by flocculating and reflocculating the host structure. Electro intercalation is yet another method, in which the host lattice serves as the cathode of an electrochemical cell. Electrochemical lithium intercalation occurs together with compensating electrons leading to the formation of vanadium bronzes as follows:



Whittingham et al. have presented comprehensive reviews on lithium battery cathode materials including lithium metal oxides and vanadium oxides. For Li-ion intercalation applications,

vanadium pentoxide offers the essential advantages of low cost, abundant source, easy synthesis, and high energy densities<sup>16</sup>. Figure-2 represents the structure of the  $\text{V}_2\text{O}_5 \cdot \text{H}_2\text{O}$  xerogel (polyhedra and ball-stick model) as revealed by PDF analysis. Characteristic distances are shown in figure-2. Water molecules are round dots between the layers. Crystalline  $\text{V}_2\text{O}_5$  is an ordered assembly of single layers of  $\text{V}_2\text{O}_5$ . The  $\text{V}_2\text{O}_5 \cdot n\text{H}_2\text{O}$  xerogel is a stack of long ribbonlike slabs which are bilayers of single  $\text{V}_2\text{O}_5$  layers made up of square pyramidal  $\text{VO}_5$  units, as shown in Figure-2. The closest distance between the bilayers is about 11.5 Å. When the xerogel intercalates or extracts guest species, this distance expands or contracts correspondingly. The distance between the two single sheets of  $\text{V}_2\text{O}_5$  making up the bilayer slab is approximately 2.90 Å. The coordination environment of V atoms in each bilayered slab can be taken as octahedral<sup>17</sup>. The  $\text{VO}_5$  octahedra share edges to form double chains propagating down the b axis. These double chains then arrange in parallel and side by side via interchain V-O bonds by sharing corners of octahedra to form the slab. Similarly, crystalline  $\text{V}_2\text{O}_5$  consists of monolayered slabs composed of parallel double chains. On the basis of such one-dimensional chain based slab structure, needlelike crystal growth appears in crystalline  $\text{V}_2\text{O}_5$  and long nano ribbons are formed in the  $\text{V}_2\text{O}_5 \cdot n\text{H}_2\text{O}$  xerogel<sup>18</sup>. Figure-3 presents the crystal structure of  $\text{V}_2\text{O}_5$ . The apical V-O bond distance is much shorter than the four other distances and corresponds to a double bond. The layered structure of  $\text{V}_2\text{O}_5$  illustrates a two-dimensional character for this material; however, the structure of  $\text{V}_2\text{O}_5$  can be described as distorted  $\text{VO}_6$  octahedral as well. The structural anisotropy of this material is illustrated by the very large length of the sixth V-O bond which gives rise to the ability to insert guest species in perovskite-like cavities<sup>19</sup>.



**Figure-2**  
 Structure of the  $\text{V}_2\text{O}_5 \cdot \text{H}_2\text{O}$  xerogel (polyhedra and ball-stick model) as revealed by PDF analysis. Characteristic distances are shown. Water molecules are round dots between the layers

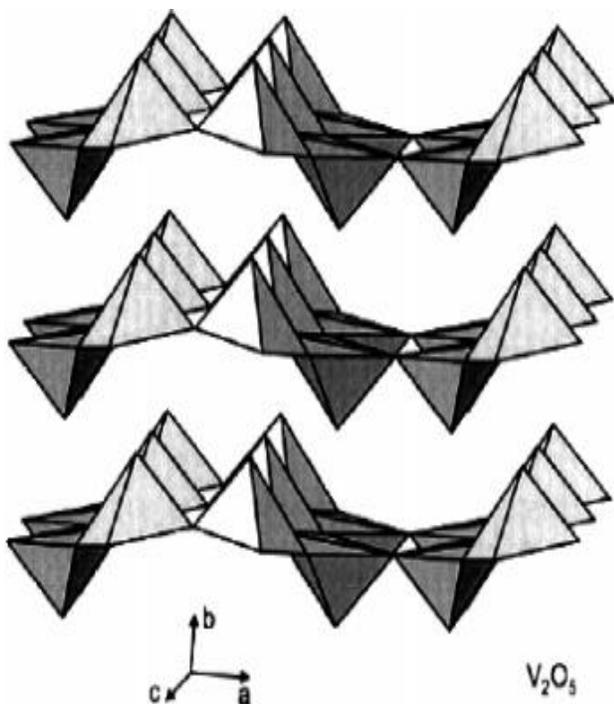


Figure-3

Crystal structure of  $V_2O_5$  consisting of layers of  $VO_5$  square pyramids that share edges and corners with the apical V-O bond distance being much shorter than the four other distances and corresponding to a double bond

### Nanostructured Vanadium Oxide

In order to fabricate oxide nanostructures of various dimensionalities and a high degree of structural order it is essential to balance the thermodynamic and kinetic forces that drive the chemistry and the mass transport associated with the formation of the oxide layer, particularly when the metal of interest exhibits a large range of oxidation states, as does vanadium. The thermodynamic forces are given by the materials chosen and include the surface and interface energies of the metal (oxide) surface and the oxide-metal interface, whereas the kinetic effects can be adjusted by varying the experimental deposition parameters, such as substrate temperature, oxygen pressure and evaporation rate<sup>20</sup>.

The vanadium oxide nanostructures considered in this article have been grown by physical vapour deposition (PVD) onto atomically clean Rh (111) single-crystal metal surfaces. Three different kinetic routes were used for the preparation of the nanostructures. In the reactive evaporation (RE) method vanadium metal was evaporated in an oxygen atmosphere (at typically  $p(O_2) = 2 \times 10^{-7}$  mbar) onto the clean metal substrate, kept at elevated temperature (up to 400°C) to provide the mobility necessary to obtain a high degree of structural order in the oxide over layer. To prevent oxide reduction or decomposition following the vanadium deposition the sample was cooled down to room temperature in an oxygen atmosphere.

In our studies vanadium was evaporated from an electron beam evaporator (Omicron) and the deposition rate was monitored by a quartz crystal microbalance; a rate of 0.2 monolayer  $\text{min}^{-1}$  was typically employed. The vanadium oxide coverage is given in monolayer equivalents (MLE), where 1 MLE contains the same number of vanadium atoms as one monolayer of Rh (111) atoms. Alternatively, the post-oxidation (PO) method was used, which consists of deposition of vanadium in ultra-high vacuum (UHV) onto the metal substrate, kept at room temperature to prevent a possible alloying with the vanadium metal. Subsequently the vanadium layer was oxidized by heating the sample in an oxygen atmosphere<sup>21</sup>. For the generation of 0D and 1D oxide nanostructures a third technique, called post-deposition (PD), was employed, where the metal substrate is initially pre-covered by a layer of chemisorbed oxygen, the amount of which is known (for example, the O ( $2 \times 1$ ) chemisorbed phase on Rh (111) contains 0.5 ML oxygen atoms) and these oxygen species serve as a reservoir for the subsequent oxidation of vanadium. Metallic vanadium is deposited onto this surface in UHV at room temperature and is followed by a flash to typically 250°C to lower the reaction barrier for the vanadium oxidation. Variable-temperature scanning tunneling microscopy (STM) was the main instrumental tool for the characterization of the morphology and the atomic structure of the vanadium oxide nanostructures. The experiments were carried out in a custom-designed UHV system with a typical base pressure of  $5 \times 10^{-11}$  mbar, described elsewhere. To model the structure of the various low-dimensional vanadium oxide phases density functional theory (DFT) calculations were performed using the Vienna initio simulation package (VASP), as described in more detail in<sup>22</sup>.

Vanadium pentoxide nanorod arrays have been grown inside 200 nm diameter PC templates with the assistance of an electric field in three different media, i.e., a  $VO^{2+}$  solution (route A), a  $VO^{2+}$  solution (route B), and a  $V_2O_5$  sol (route C). The pure orthorhombic phase of  $V_2O_5$  was obtained by sintering the nanorod arrays at 485°C in air for one hour, and the PC membrane was pyrolyzed as a result. It is worth noting that, under otherwise comparable growth conditions, the nanorods grown by electrochemical deposition showed negligible shrinkage, whereas those grown via a pH change showed a noticeable 15% lateral shrinkage; moreover, the nanorods grown from sol electrophoretic deposition showed a substantial lateral shrinkage of 50%. Such significant differences in lateral shrinkage of the three nanorods upon firing can be explained by their distinctively different growth mechanisms<sup>23</sup>.

### Applications of Vanadium Pentoxide

Vanadium Pentoxide, one among the transition metal oxides, is an interesting material for scientific and technological applications. It is a low mobility semiconductor with predominantly n-type conductivity.  $V_2O_5$  exhibits an orthorhombic layered structure and can be prepared in thin film form by a variety of deposition techniques. As a thin film, it

exhibits multi colored electrochromism and has high potential for use in electrochromic display devices, color filters and other optical devices. Bulk and thin film  $V_2O_5$  with vanadyl oxygen vacancies have been used as an oxidation catalyst. As a functional inorganic material,  $V_2O_5$  can be used in gas sensors and electrochromic cells. High values of its electrochemical potential difference with lithium and its specific energy density made it suitable as a cathode material in solid state lithium microbatteries.

Recent applications of  $V_2O_5$  thin films are as follows: i. Vanadium pentoxide is a good catalyst in several chemical reactions. For example in contact process for sulfuric acid preparation,  $V_2O_5$  used as catalyst and also in thin film form it enhances the oxygenated and dehydrogenated reactions. ii. These oxide films are utilized as oxygen and pH sensors and IR detectors. iii. These vanadium oxides are used to develop both p-type and n-type semiconductors depending on substrate and temperature. iv. Vanadium oxides are used as optical switching devices, for example at high temperatures  $VO_2$  is opaque to infrared regions. v. These sensors are good hydrogen sensors depending on the gasochromism property for sensing hydrogen in organic gases. vi. Vanadium Oxide is a good cathodic material for solid state micro batteries as thin layer. For example Li ion micro battery.

In metallurgy, vanadium pentoxide is used to produce ferrovanadium, which increases the strength of steel. The strength of these vanadium alloys and their resistance to corrosion lends their application to the production of automobiles, tools and engines. Vanadium plays a critical role in the titanium alloys used in the aerospace industry. Vanadium pentoxide finds use in the chemical industry as a catalyst for the production of sulfuric acid and other chemicals, insecticides and photographic chemicals<sup>24</sup>. Due to its high coefficient of thermal resistance, vanadium (V) oxide finds use as a detector material in bolometers and micro bolometer arrays for thermal imaging<sup>25</sup>. It also finds application as an ethanol sensor in ppm levels (up to 0.1 ppm). Maleic anhydride is another important industrial material, used for the manufacture of polyester resins and alkyd resins. Vanadium (V) oxide can catalyze its production from a variety of organic starting materials such as n-butane, furfural and benzene, the last of which is the usual commercial method. In a related process, phthalic anhydride, used for making plasticizers for PVC manufacture, may be produced by  $V_2O_5$  catalyzed oxidation of ortho-xylene or naphthalene at 350–400 °C<sup>26-28</sup>.

## Conclusion

Vanadium Pentoxide, one among the transition metal oxides, is an interesting material for scientific and technological applications. It is a low mobility semiconductor with predominantly n-type conductivity.  $V_2O_5$  exhibits an orthorhombic layered structure and can be prepared in thin film form by a variety of deposition techniques. As a thin film, it

exhibits multi colored electrochromism and has high potential for use in electrochromic display devices, color filters and other optical devices. Bulk and thin film  $V_2O_5$  with vanadyl oxygen vacancies have been used as an oxidation catalyst. Vanadium pentoxide with a layered structure is promising for smart window applications.  $V_2O_5$  crystallizes with an orthorhombic unit cell and belongs to  $P_{mmm}$  space group with lattice parameter  $a = 11.510 \text{ \AA}$ ,  $b = 3.563 \text{ \AA}$ ,  $c = 4.369 \text{ \AA}$ , where the b and c are often interchanged. The stoichiometry of  $V_2O_5$  is considered as deformed octahedral  $VO_6$  which serves as the building block of the  $V_2O_5$  structure. As a thin film, it exhibits multi colored electrochromism and has high potential for use in electrochromic display devices, color filters and other optical devices. Bulk and thin film  $V_2O_5$  with vanadyl oxygen vacancies have been used as an oxidation catalyst. In this paper the detailed technological aspects of properties, different structures of  $V_2O_5$  as candidate cathode material for the fabrication of all solid state lithium ion batteries with wide applications of  $V_2O_5$  films as electrochromic cells and gas sensors are reported.

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