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Review article

Effect of thickness on the optical, structure, and electrical properties of vanadium oxide thin films

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ABSTRACT

Vanadium pentoxide (V_2O_5) thin films on glass, made using RF magnetron sputtering at power level (100 W) and thicknesses (150, 250, and 350 nm) at room temp have been prepared. We checked out how film thickness impacts the structure, light interaction, and electrical behavior of the V_2O_5 films. X-ray diffraction (XRD) showed that an orthorhombic V_2O_5 thing formed. Atomic force microscopy (AFM) showed surfaces got smoother and less rough as the films got thicker. UV–Vis spectroscopy showed less light got through as films thickened. The optical band gap got wider, going from 2.2 eV (150 nm) to 2.4 eV (250 nm), and then 2.6 eV for the 350 nm film. Electrical stuff: resistivity went way down from 1.4×10^{-3} Ω.cm at 150 nm to 2×10^{-4} Ω.cm at 350 nm. Conductivity went up from 1×10^{3} $(\Omega.cm)^{-1}$ to over 7×10^{3} $(\Omega.cm)^{-1}$. Hall effect results said all films were n-type, probably because of oxygen gaps. Basically, how thick these V_2O_5 films are really changes how they work. This is key if you wanna use them in optoelectronic devices, sensors, and electrochromic systems.

Keywords: V_2O_5 thin films, magnetron, sputtering, thickness

INTRODUCTION

Vanadium oxides are a varied bunch of materials, each with its own special set of properties [1]. The usual suspects are VO, VO_2, V_2O_3, V_4O_9, and V_2O_5, with vanadium pentoxide (V_2O_5) being the most stable [2]. These oxides are cool because they can switch phases back and forth, like going from a semiconductor to a metal [3]. This opens doors for all sorts of uses in electronics and optoelectronics [4]. V_2O_5 stands out because it's got a fairly wide optical band gap, about 2.0 to 2.6 eV [5]. Plus, vanadium can exist in different oxidation states (V^{3+}, V^{4+}, V^{5+}) [6]. It's also very stable, both chemically and thermally, has a layered crystal structure, and some interesting thermoelectric traits [7].

V_2O_5 thin films are used a lot in solid-state devices like smart windows, color filters, gas sensors, thin-film lithium-ion batteries, and optical displays because of these traits [8]. How well these films work depends a lot on how they're made and the conditions when they're deposited. Usual ways to make V_2O_5 thin films are vacuum evaporation [9, 10], thermal oxidation [11], RF and DC sputtering [12, 13], pulsed laser deposition (PLD) [14], and chemical vapor deposition (CVD) [15]. Each way changes the film's look, crystal structure, ingredients, and how well the device works overall.

In this study, V_2O_5 thin films on glass using RF magnetron sputtering with the power to 100 W have been synthesized. This gave us films of different thicknesses: 150, 250, and 350 nm. We wanted to see how thickness affects what the V_2O_5 films look like (optics), how they're put together (structure), and how well they conduct electricity (electrical properties). So, we used X-ray diffraction (XRD) to check out their crystal structure, Atomic Force Microscopy (AFM) to see what the surface looks like, UV-Vis spectroscopy to check out the optical stuff, and Hall Effect measurements to figure out how they conduct electricity.

EXPERIMENTAL

We made vanadium pentoxide films using a method called RF magnetron sputtering. We took a 5 cm target and zapped it with 100W of power. Basically, we shot high-purity vanadium (99.99%) at cleaned glass. The machine we used was a stainless steel cylinder (250 mm tall, 230 mm wide). We put all the glass on a 100 mm wide circular holder, about 30 mm away from the target. We used really pure argon gas (99.999%) to make it work. First, we sucked all the air out of the machine down to 5.5×10-6 mbar.

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Then, we pumped in the argon. We made films with thicknesses from 150 to 350 nm by changing the sputtering time. After making them, we checked out the films' optical, structural, and electrical stuff. We used X-ray diffraction (Shimadzu - XRD6000) to see how the crystals were arranged. We used a UV-VIS-IR spectrophotometer (Shimadzu-3600) to see how light passed through the films. An Atomic Force Microscope (AFM) helped us to look at the surface of the films and their structural details.

RESULTS AND DISCUSSION

STRUCTURAL PROPERTIES

To figure out the crystal structure of the vanadium pentoxide thin film, we looked at its phase. When X-rays hit the film, peaks showed up at certain angles because of Bragg's reflection on the crystal surface [16]. Fig. 1 shows how X-rays diffract on the vanadium oxide film at room temperature and at different thicknesses (150, 250, and 350 nm). It's obvious that the film on the glass was amorphous since there were no diffraction peaks for V2O5. Our results matched well with standard data file [41-1426 JCPDS card] [17]. The differaction angles are 12.55, 17.54, 22.9, 24.1, 25.3, 29.5, 36.69, and 38.35, with the corresponding planes are (001), (101), (110), (301), (400), (310), (002), (211). Crystal system is Orthorhombic, space group: Pmmn (No. 59), and lattice parameters (a ≈ 11.51 Å, b ≈ 3.56 Å, and c ≈ 4.37 Å). Scherer's formula has been utilized to get the average crystal size of the films [18]:

$$D = \frac{k\lambda}{\beta \mathrm{Cos}\theta} \quad (1)$$

D is the crystal size, k is 0.9, λ is the x-ray wavelength, θ is the Bragg diffraction angle in degrees, and β is the FWHM of the chosen peak. The average crystal sizes for the 150 nm, 250 nm, and 350 nm vanadium pentoxide thin films were 60.98 nm, 50.97 nm, and 44.35 nm, respectively.

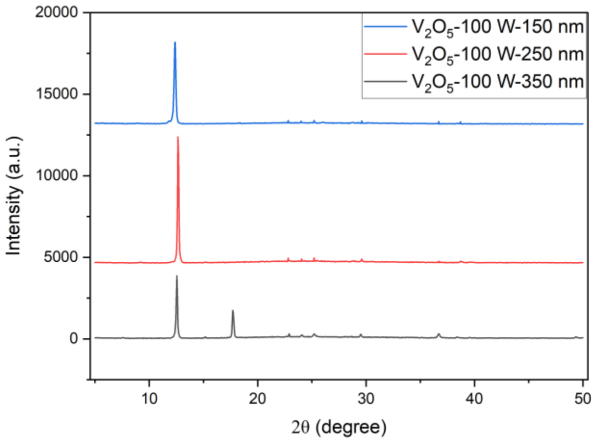

Fig. 1 The XRD patterns of V_2O_5 thin films (100 W) with different thicknesses (150, 250, and 300 nm).

MORPHOLOGY

AFM has been utilized to check out how the V_2O_5 thin films looked (see Fig. 2). It's easy to see that all the films have a smooth surface, with crystal grains in a nano size. When we looked at the surface, we saw that the vanadium oxide's grain size is nano. The film's surface gets rougher as it gets thicker. So, the thicker the film, the bigger the particle size. The particle sizes were 100.23 nm, 90.45 nm, and 80.44 nm for films that were 100 nm, 200 nm, and 300 nm thick. When the grain size goes up, there are fewer grain boundaries, which lowers the barrier between them (see Table 1).

We checked out vanadium pentoxide (V_2O_5) thin films made using RF sputtering at 100 W. We varied how thick the films were—150 nm, 250 nm, and 350 nm—and saw how it changed the surface and crystal size. Table 1 shows there's a pattern: as the films got thicker, the surfaces got smoother. The average roughness (R_a) went from 13.13 nm at 150 nm to 8.33 nm at 350 nm. Similarly, the root mean square roughness (R_{rms}) went down from 15.10 nm to 10.69 nm. It looks like thicker films end up smoother because at first, the film grows in little islands, but as it gets thicker, it forms a continuous layer. As the film builds up, atoms move around and join together better, making the surface smoother and more tightly packed. At the same time, the crystal size got smaller as the film got thicker. It went from 100.33 nm at 150 nm to 60.14 nm at 350 nm. Maybe this happens because more crystals start to form as the film gets thicker. When the film is thin, there are fewer spots for crystals to start growing, so they end up bigger. But when the film is thicker, more spots appear, so you get smaller crystals with more boundaries between them. Also, atoms can't move around as freely when the film is thick, which could also keep the crystals from growing bigger. So,

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making the film thicker with the same sputtering power gives you a smoother surface but smaller crystals. This could be good for things that need smooth, dense films, like electrochromic devices, optoelectronics, and energy storage stuff. But, the smaller crystal size might change how well the film conducts electricity or lets light through, so you'd need to keep that in mind when designing stuff.

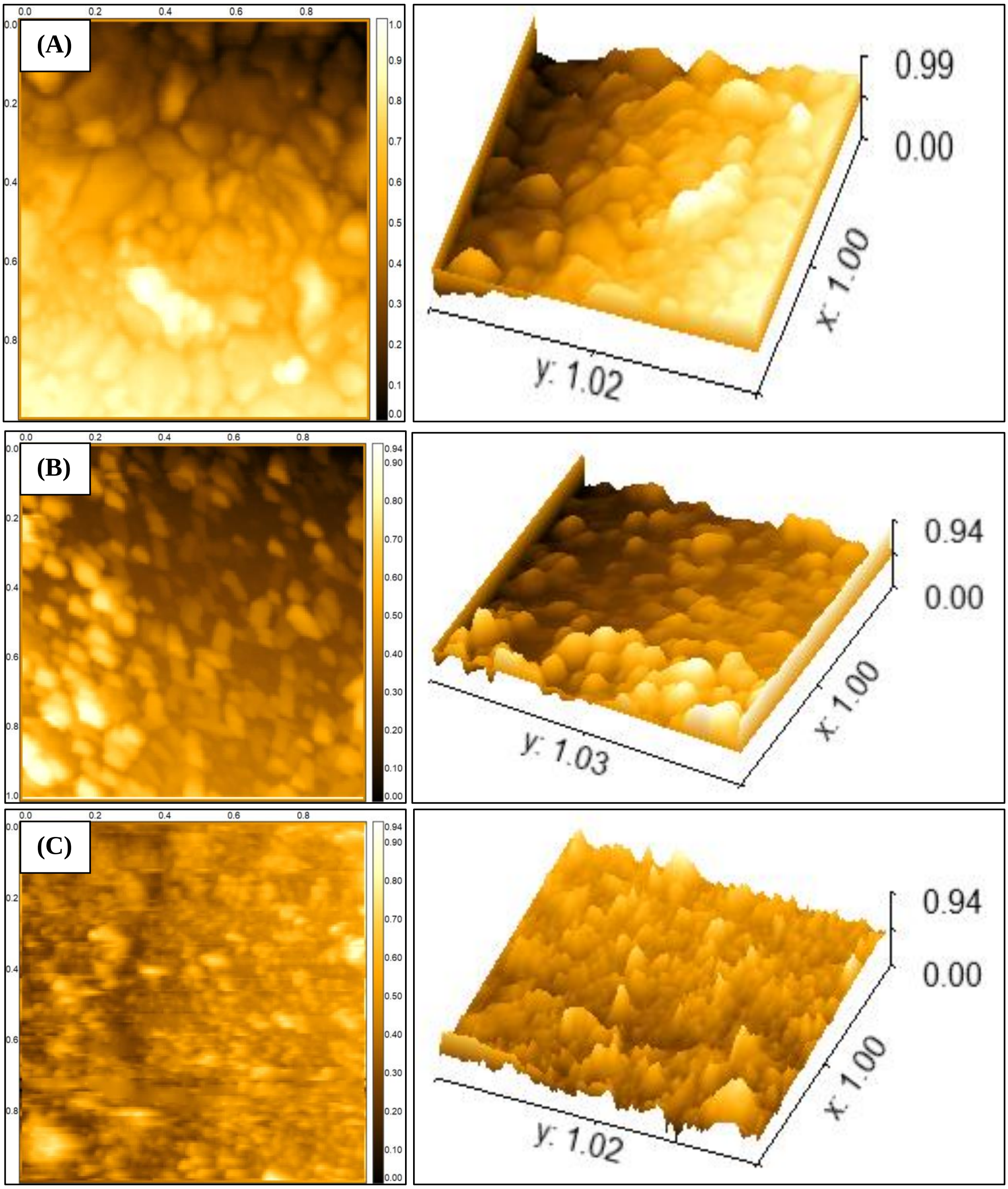

Fig. 2: AFM images of V_2O_5 thin films made with RF (100 W) at different thicknesses: (A) 150 nm, (B) 250 nm, and (C) 350 nm.

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Table 1: The values of average surface roughness, root mean square and grain sizes for V_2O_5 thin films at 100 W with different thicknesses 150, 250 and 350 nm.

Film thickness (nm)	R_{ave} (nm)	R_{rms} (nm)	Crystallite size (nm)
150	13.13	15.1	100.33
250	11.52	13.66	80.84
350	8.33	10.69	60.14

SCANNING ELECTRON MICROSCOPY (SEM) RESULTS

Fig. 3 shows SEM images of V_2O_5 thin films made by R.F. sputtering on glass, with different thicknesses. You can see that all the films have pretty consistent and even surfaces. They're dense and stick to the glass well, with no cracks. The grain sizes we got from the images are 100.33 nm, 80.84 nm, and 60.14 nm for thicknesses of 100, 200, and 300 nm, respectively. The SEM images show that particle size goes up as annealing temperature and thickness increase, probably because there are fewer grain boundaries in the V_2O_5 thin film. These findings line up with what we saw in the XRD and AFM results. The average grain size, calculated using Scherer's-Oebye formula, is smaller than what we got from AFM & SEM. This suggests the grains are likely made up of many smaller crystallites.

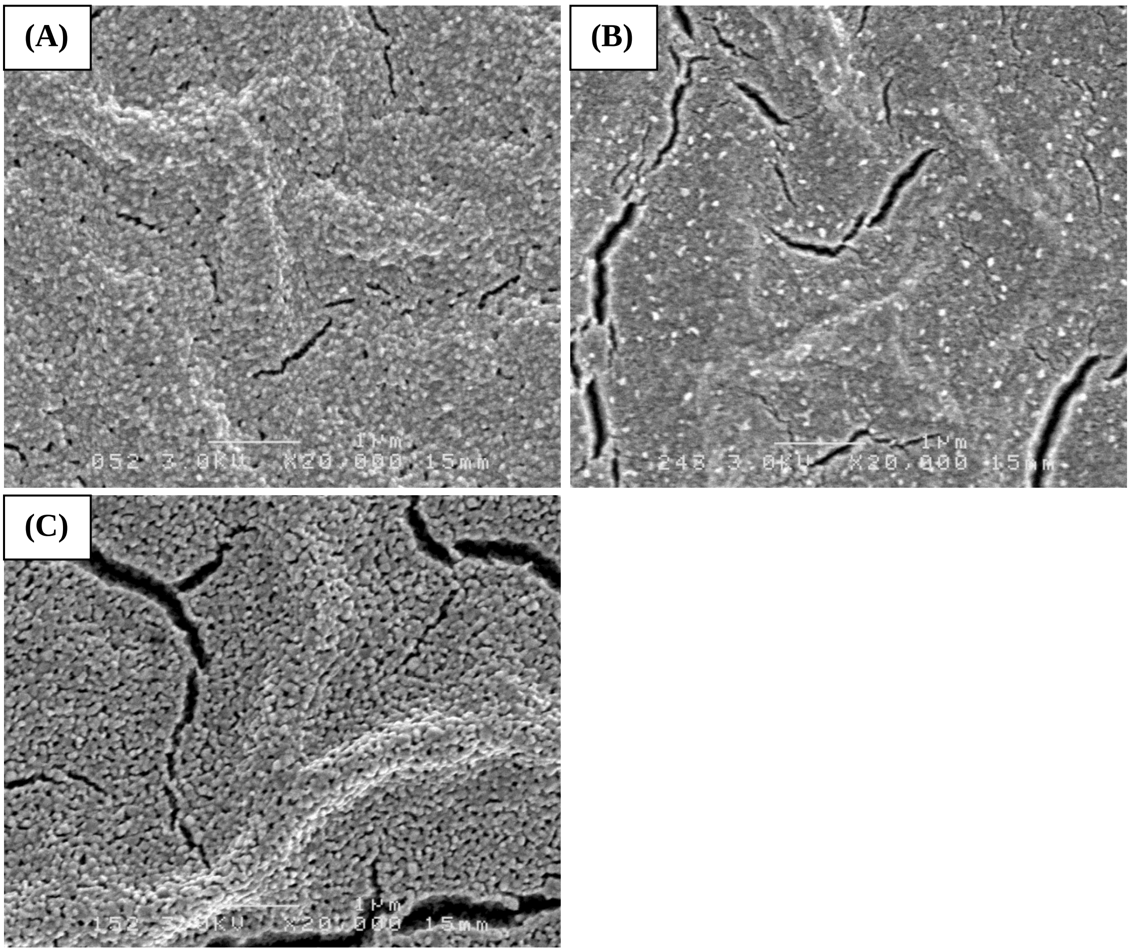

Fig. 3. SEM image of V2O5 thin film prepared by RF sputtering (100 W) at different thicknesses and after annealing (A) l50 (B) 250, and (C) 350 nm.

OPTICAL PROPERTIES

Fig. 4 presents the transmittance spectra of vanadium pentoxide (V_2O_5) thin films deposited on glass substrates, with thicknesses of 150, 250, and 350 nanometers. The optical transmittance decreases as the film thickness increases, as illustrated in the figure. This reduction in transmittance occurs because thicker films contain a greater density of absorbing material, leading to increased light absorption and reduced transmission. Additionally, the increased number of atomic layers in thicker films results in more photon interactions, further limiting the amount of light that can pass through the material.

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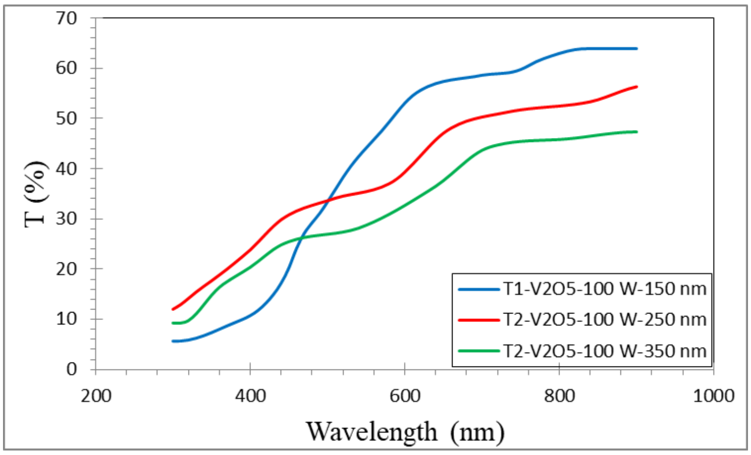

Fig. 4. Optical transmittance of Vanadium Pentoxide (V_2O_5) films utilizing RF sputtering (100 W) as a function of thickness.

The optical energy band gap (E_g) of V2O5 films by looking at where the thin films start to absorb light. For direct transitions that are allowed, there's a relationship between α (absorption coefficient) and photon energy (hυ) called the Tauc relationship [19]:

$$(\alpha h\upsilon)^2 = A\,(E_g - h\,\upsilon) \tag{2}$$

where E_g is the energy band gap, A is a constant for direct transitions, υ is the frequency of the incoming light, and h is Planck's constant. Fig. 5 shows how $(\alpha h\upsilon)^2$ relates to photon energy (hυ). One can see also that the optical band gap of the V_2O5 samples goes up bit by bit from 2.2 eV to 2.4 eV, then to 2.6 eV. This might have to do with the grain size getting smaller.

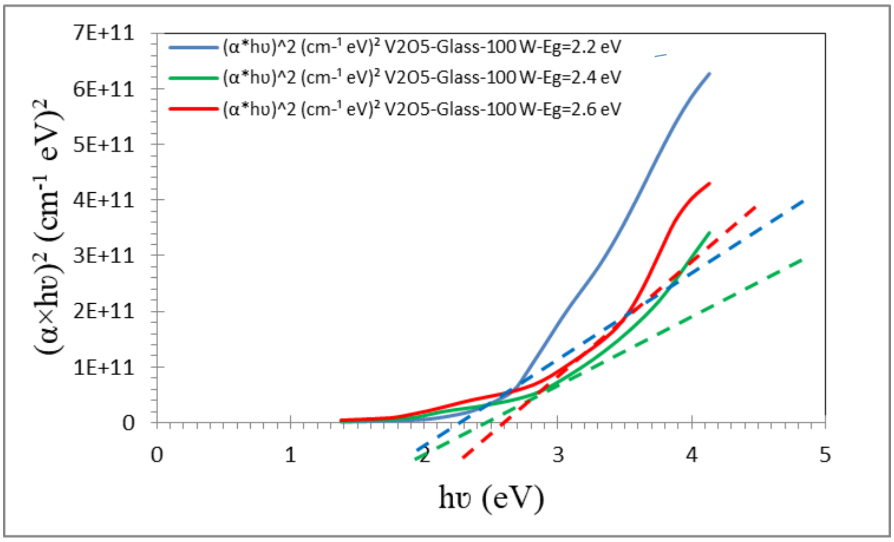

Fig. 5. (hυ) vs. $(\alpha h\upsilon)^2$ of V_2O_5 films at different RF power (100 W) as a function of thickness (150, 250, and 350 nm).

ELECTRICAL PROPERTIES

Fig. 6 shows how the electrical resistance (ρ) and electrical conductance (σ) of vanadium pentoxide (V_2O_5) films change with thickness (150, 250, and 350 nm). The results show that as the film gets thicker, its resistance goes down. To be exact, the resistance drops from around 1.4 × 10-3 Ω.cm at 150 nm to about 2 × 10-4 Ω.cm at 350 nm. So, thicker films seem to conduct electricity better.

On the other side, how well electricity flows goes up a lot as the film gets thicker. It jumps from about 1 × 10^3 (Ω.cm)-1 for the thinnest one to more than 7 × 10^3 (Ω.cm)-1 for the thickest. This boost probably happens because the film is structured better and there's less stuff getting in the way of the electrons. As the film gets thicker, it seems to form a more solid and crystal-like structure, meaning fewer flaws and boundaries that would stop the flow of electricity.

The behavior of electricity acts in these films depends on a few things. When the films are thin, the surface messes with the electricity flow, so they don't conduct as well. But when they're thicker, they act more like a solid chunk, which lets electricity

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move through them more easily. Plus, growing thicker layers of V_2O_5 seems to make them purer and more balanced, which helps them conduct even better.

Hall effect tests showed that all the V_2O_5 films put on glass act like n-type conductors. This means electrons are the main charge carriers. V_2O_5 films often act this way when they don't have enough oxygen. The missing oxygen creates spots that donate electrons, which helps the film conduct electricity. This shows how important it is to control film thickness if you want to change the electrical properties of V_2O_5 films. This adjustment is useful for electrochromic devices, sensors, and thin-film transistors.

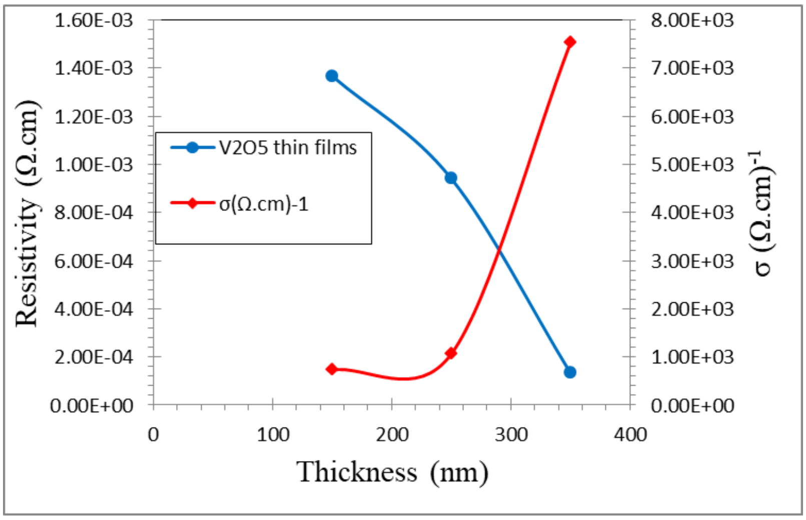

Fig. 6. The resistivity and conductivity of V_2O_5 thin films at 100 W power with different thickness (150, 250, and 300 nm).

SENSITIVITY MEASUREMENTS

To get better gas sensing, you need to make really thin films that have a high surface area compared to their volume. Having lots of tiny crystal bits makes the material porous with a big surface, which is important for gases to stick to it. The sensitive of vanadium oxide thin films can be calculated using [equation follows] [20]:

$$S = \frac{(R_{gas} - R_{air})}{R_{air}} \times 100\% \quad (3)$$

where the sensitivity (S) value (in %), and the resistance in the gas environment (R_{gas}), and R_{air} (the resistance of the sensor in air).

Fig. 7 and Table 2 illustrates the gas sensitivity response of vanadium pentoxide (V_2O_5) thin films with different thicknesses (150, 250, and 350 nm) deposited at 100 W RF sputtering power. The sensitivity (%) is plotted as a function of time (seconds), showing the films' dynamic response to gas exposure and recovery.

From the figure, it is evident that all films exhibit a rapid increase in sensitivity upon exposure to the target gas, followed by a gradual decrease as the gas is removed or desorbed. The peak sensitivity values are clearly thickness-dependent. The 150 nm film (blue curve) demonstrates the highest sensitivity, reaching approximately 66%, while the 250 nm (green) and 350 nm (red) films peak at around 50% and 40%, respectively. This trend suggests that thinner films possess enhanced gas sensing capabilities compared to thicker counterparts.

The superior sensitivity of the 150 nm film can be attributed to its higher surface-area-to-volume ratio, which facilitates more active sites for gas adsorption. Additionally, thinner films may allow faster diffusion of gas molecules to and from the surface, resulting in sharper response and recovery behaviors. In contrast, the thicker films exhibit lower peak sensitivities and slower response dynamics, likely due to reduced surface accessibility and longer diffusion paths within the bulk of the material.

After reaching their respective peaks, all films show a decrease in sensitivity as the gas begins to desorb and the sensors return to their baseline state. The rate and completeness of recovery also appear influenced by film thickness, with thinner films showing a more pronounced decline in sensitivity post-exposure.

These results highlight that film thickness plays a critical role in determining the gas sensing performance of V_2O_5 thin films. Thinner films offer higher sensitivity and faster response characteristics, making them more suitable for applications requiring rapid and accurate gas detection.

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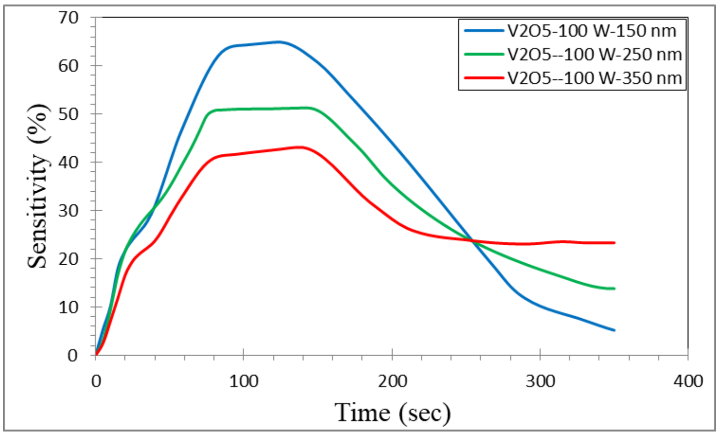

Fig. 7. The variation of sensitivity with time for V_2O_5 thin film (thickness 150, 250, and 300 nm) for NH_3 gas.

Table 2. The values of sensitivity for thicknesses 150, 250, and 350 nm of V_2O_5 thin films

100 W	
Thickness (nm)	Senility (%) for NH_3 gas
150	65
250	50
350	40

CONCLUSION

Vanadium pentoxide (V_2O_5) thin films deposited by RF sputtering at 100 W were systematically studied to evaluate the effects of film thickness (150, 250, and 350 nm) on their structural, optical, electrical, and gas sensing properties. The surface morphology analysis showed that increasing film thickness resulted in smoother surfaces and smaller crystallite sizes, indicating improved film uniformity and density. Optical transmittance spectra revealed a decrease in transparency with increasing thickness due to enhanced light absorption, which is attributed to the greater number of atomic layers in thicker films. Additionally, the optical band gap of the V_2O_5 samples was found to increase with thickness, rising from 2.2 eV for the 150 nm film to 2.4 eV at 250 nm and reaching 2.6 eV at 350 nm. Electrical measurements demonstrated that resistivity decreased significantly with increased thickness, dropping from 1.4×10^{-3} $\Omega\cdot$cm at 150 nm to 2×10^{-4} $\Omega\cdot$cm at 350 nm, while conductivity increased from 1×10^{3} $(\Omega\cdot\text{cm})^{-1}$ to over 7×10^{3} $(\Omega\cdot\text{cm})^{-1}$, suggesting improved charge transport in thicker films. Hall effect measurements confirmed that all films exhibited n-type conductivity, likely due to oxygen vacancies acting as donor states. Gas sensing tests showed that thinner films, particularly the 150 nm sample, displayed the highest sensitivity (up to ~66%), along with a faster response, owing to a higher surface-to-volume ratio and more active adsorption sites. In contrast, thicker films exhibited reduced sensitivity and slower recovery. Overall, the results confirm that film thickness critically influences the multifunctional performance of V_2O_5 thin films, and that optimizing thickness is essential for tailoring their behavior in applications such as gas sensors, electrochromic devices, and optoelectronics.

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