Recent Progress and Prospect of Electrochromic Metal Oxides

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Abstract: Electrochromic metal oxide materials, which have high optical contrast and high environmental stability, are widely used in smart Windows, capacitors and other fields. Compared with organic polymer materials, metal oxide materials have higher stability and better optical performance, making them suitable for long-life devices. This paper systematically reviews the latest research progress of metal oxide electrochromic materials, with a focus on their applications in smart Windows, high-resolution displays, flexible electronics, and energy storage. Metal oxides (such as WO_3, NiO) have become the core of research due to their excellent optical modulation capabilities (up to 75% ΔT), high environmental stability (78% performance after 3500 cycles), and diverse preparation processes (sol-gel, lithography). Nanostructure design (MXene/WO_3 microcavities) and photoelectro-synergistic self-healing technology significantly improved response speed (coloring time <1 second) and device lifetime (no decay after 1000 cycles). In the future, challenges such as large-scale fabrication, cost reduction, extreme environment stability and multi-functional integration need to be overcome to promote their commercial application in smart buildings and wearable devices.

1 INTRODUCTION

Electrochromic materials have become a research hotspot in recent years due to their broad application prospects in smart Windows, energy-saving displays, flexible electronics, and other fields. Traditional electrochromic materials are divided into two major categories: organic and inorganic. Inorganic metal oxides (such as WO_3, NiO, IrO_2, etc.) have become the mainstream research direction due to their excellent optical modulation ability, environmental stability, and diverse and flexible preparation processes.

Unlike the traditional preparation process, Gu et al. (2025) developed direct lithography technology to achieve high-resolution patterning of WO_x nanoparticles, which gave them the characteristics of fast response, high coloring efficiency, and good cycling stability. In addition, Ren (2023) synthesized Nb18W16O93 bimetallic oxides by the sol-hydrothermal method and prepared thin films by the spraying method, and studied the effect of electrolyte cations on the electrochromic properties of the material, achieving extremely high optical modulation range and cycling stability. In the study of microcavity structures, Wang et al. (2024) developed the synergism of electrochromism and rapid deformation through the study of Fabry- Perot microcavity structures of MXene/WO bilayer films, and achieved the results of a maximum bending Angle of 95°, a response time of 10 seconds and 1000 cycle stability.

Although many studies have made progress in preparation methods and performance optimization, there are still many challenges in the display field, environmental stability, and the preparation process. Therefore, this paper aims to review the latest research progress of electrochromic metal oxide materials, clarify their advantages in optical modulation, environmental stability, and preparation process, and provide references for innovative applications for researchers in related fields. In addition, expectations are presented for its development trends and the commercial application of related devices.

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2 ADVANTAGES OF METAL OXIDE MATERIALS IN ELECTROCHROMISM

2.1 Excellent Optical Modulation Ability and Color Diversity

In the field of electrochromism, metal oxide materials refer to a class of materials whose optical properties (such as color, transparency, etc.) are reversibly regulated under the action of an electric field. These materials are mostly transition metal oxides or their derivatives, such as WO_3, TiO_2, MoO_3, etc., which have the characteristics of long-lasting color change, good stability, and excellent optical memory.

Compared with traditional electrochromic materials such as organic polymers, metal oxides (such as WO_3, NiO, V_2O_5) can not only achieve reversible optical changes through dual implantation/deimplantation of ions and electrons, but also have a wide spectral modulation range. In Jia et al. (2023), for example, electrochromic devices based on Nb: TiO_2 nanocrystals still achieved a spectral modulation of more than 64% at 800-2000 nm, and spectral modulation in the visible light band was also achievable at a high potential of 3-4 V. Unlike traditional electrochromic materials, the transmittance variation range of Prussian blue is usually less than 50%, while tungsten oxide (WO_x) can be transformed from transparent to dark blue under electrical stimulation, with an optical modulation amplitude of up to 55.9% (Gu et al., 2025). Bimetallic oxides (such as NiMn-LDH) further expand the light modulation ability through elemental synergies and achieve neutral tones (such as brownish black and pale yellow) to avoid visual fatigue caused by traditional blue tones (Feng, Ma, & Wang, 2024). In addition, rare earth metal oxides (e.g., $Ce_4W_9O_{33}$) can independently regulate visible light and near-infrared light through surface plasmonic resonance effects to accommodate different environmental requirements (Guo et al., 2024).

2.2 High Environmental Stability

Traditional electrochromic materials such as polyaniline and polypyrrole are prone to structural fracture or side reactions during repeated REDOX processes, resulting in performance degradation. In addition, humidity, temperature, and other factors can accelerate the decomposition of the material. Metal oxides, due to their inorganic properties, have excellent chemical stability and durability. Doped metal oxide nanocrystals, such as ITO and AZO, due to their special chemical composition and structure, can maintain good performance under environmental factors such as air and humidity, and are not easily oxidized or corroded. For example, tungsten oxide nanoparticles were used in cyclic voltammetry (CV) to produce electrochromic devices based on photolithography WOx films. The results of maintaining its electrochemical reduction and reoxidation performance after 3,600 cycles are as follows: The device underwent a complete coloring and bleaching process during the cycle, and the optical modulation performance was well maintained, with a residual optical modulation limit of 22.4% and a maintenance ratio of 78%, indicating good environmental stability (Gu et al., 2025).

2.3 The Preparation Process Is Flexible and Highly Compatible

Metal oxides have shown excellent process advantages in the field of electrochromic materials. Because of its strong structural controllability, it can not only precisely control the microstructure through the sol-gel method, but also achieve the growth of specific morphology and obtain uniform films through the hydrothermal method and sputtering method, and flexibly adjust physical and chemical properties according to different application scenarios. Take $WO_x(0<x\leq 3)$ nanoparticles as an example. They have both excellent electrochromic properties and good stability, and are favored in smart Windows, roof sunroofs, and electronic shelf labels. Especially in near-eye virtual/augmented reality display scenarios, its ultra-high resolution and ideal electrochromic performance are crucial to advancing display technology. Gu et al. (2025) could adjust the surface properties and chemical composition of WO_x NPs by selecting the appropriate photosensitive additive (PAGs) and using the in-situ ligand exchange mechanism triggered by ultraviolet radiation (UV). This indicates that in practical applications, different photosensitizers can be selected according to different requirements, and thus the physicochemical properties of WO_x NPs can be flexibly adjusted. Moreover, the direct lithography technology they developed perfectly demonstrates metal oxide preparation's flexibility, breaks traditional etching processes' limitations, and achieves high-resolution patterning with line widths less than 4μm. This innovative preparation process not only gives full play to the properties of metal oxides but also opens

up a new path for the application of electrochromic materials in fine display fields.

3 SMART WINDOWS

With the advancement of technology, the environment is being overdrawn. Smart Windows can effectively reduce building energy consumption by intelligently adjusting the intensity of indoor and outdoor light, thus maintaining the environment. Electrochromic smart Windows, which have the advantages of simple control and quick response compared to other types of smart Windows, have received extensive attention from researchers (Xie, 2024). Among them, Xie(2024) developed a tungsten oxox-based smart window (WO_3) based on the method of controlled sputtering to prepare WO_3 films at different power levels and high-temperature annealing of WO_3 films, resulting in O_3 films with an average transmittance of over 75% in the visible light range and a light modulation range of 60%-80%. The response time was reduced to less than 3 seconds.

Combining the above advantages, these tungsten-oxide-based smart Windows are suitable for buildings in high latitudes and can significantly reduce light source energy consumption. The $Nb_{18}W_{16}O_{93}$ device designed by Ren (2023) optimized ion transport through a layered structure. The sol-hydrothermal synthesis and spray fabrication method was used to obtain $Nb_{18}W_{16}O_{93}$ film with high optical modulation, fast response, and excellent cycling stability in the Zn^{2+} electrolyte system. This electrochromic metal oxide can achieve uniform and reversible color transition on large-area devices, which enhances their cycle life. Similar prospects for surface electrochromic metal oxide materials in smart Windows. Not only that, for example, the global brand Tesla's new Model S uses an electrochromic sunroof that automatically adjusts according to light, reducing the energy consumption of the in-car air conditioning by about 30 percent. Compared with traditional glass, smart Windows made of metal oxide material can make more efficient use of solar energy, reduce reliance on artificial lighting and HVAC systems, and improve the energy efficiency of buildings, all of which illustrate the promising future of smart Windows.

4 HIGH RESOLUTION DISPLAY WITH HIGH CONTRAST

Metal oxide materials also have significant advantages over traditional electrochromic materials in the display field. This is mainly reflected in high-resolution displays and high contrast, etc. Peng et al. (2025) achieved ultra-high resolution patterning of WO_x nanoparticles with line widths less than 4 microns through sol-gel synthesis, which is the highest resolution among electrochromic materials without electrochromic materials. The core technique is to prepare ultra-high resolution electrochromic patterns on tungsten oxide (WO_x) nanoparticles by direct lithography with in-situ light-induced ligand exchange (Gu et al., 2025). Not only that, the MXene/WO_3 Fabry-Perot microcavity developed by Wang et al. (2025) enables multi-color display through interference effect, allowing for continuous regulation of WO_3 thickness variation (215-293 nm) from yellow-green to purple to pink to blue, with wide CIE color gamut coverage and RGB standard coverage. And by multiple reflections of light of specific wavelengths on the upper and lower surfaces of the WO_3 layer and by changing the Angle of the incident light, constructive and destructive interferences are produced to generate specific structural colors. This interference effect not only enhances the contrast of the color but also ensures its accuracy.

5 FLEXIBLE DESIGN

5.1 Flexible Substrate Development

Compared with traditional electrochromic materials, transparent electrode materials such as ITO and FTO have poor toughness and are prone to separation from the substrate after bending, which limits the development of flexible devices. Shen (2022) selected Nafion as the polymer electrolyte, WO3 and MXene composites as the electrochromic layer, and PEDOT: PSS as the electrode material to prepare the PEDOT: PSS electrode layer on the electrochromic layer and the polymer electrolyte layer by roller coating, and dried at 50°C for 1 hour. The WO3/MXene films obtained under this condition have a high specific capacitance, a large area of cyclic voltammetry curve, strong charge storage and intercalation and migration capabilities, and can achieve wing vibration and color-changing effects under low voltage stimulation. This new type of flexible substrate not only improves the flexibility and optical performance in the field of flexible design of electrochromic materials, but also provides new ideas and methods for the development of flexible smart devices

5.2 Self-Healing Properties

The self-healing property of a flexible device refers to the ability of its material to repair itself through internal chemical or physical mechanisms after physical damage (such as scratches, breaks), restoring its original structure, conductivity, or function. Zhou et al. (2025) prepared amorphous WO_3 (300 nm) on ITO substrates by magnetron sputtering using the electro-optical co-ion release technique and conducted long-term cyclic voltammetry (CV) tests on WO_3 in $LiClO_4$-PC electrolyte (2.0-4.0 V vs. Li/Li^+) for 1000 cycles. Their photoelectro-synergistic technology (UV+ low bias) breaks down damaged phases such as Li_2WO_4 through photogenerated current, releases captured Li^+, and restores material properties. The technology is applicable to a variety of oxides and complete devices, with key parameters being wavelength (≤405 nm), power (≥100 μW/cm²), and bias (≥3.8 V). This technology provides an efficient and safe solution for extending the lifetime of electrochromic devices, as well as a safe and efficient solution for achieving the self-healing function of the devices, and an important breakthrough for the durability and sustainability development of flexible devices.

6 WEARABLE DEVICES

6.1 High Response, High Stability

Significant progress has been made in the study of metal oxide electrochromism (EC) in wearable devices. At present, response speed and cycling stability can be enhanced through material modification (such as nickel molybdate, vanadium pentoxide composite carbon materials), with a maximum light modulation retention rate of 99.4% after 1500 cycles, and neutral tones and flexible integration can be achieved (Ma et al., 2024). Metal oxides not only have the advantages of low power consumption and dynamic dimming, but also have innovations in human-computer interaction, enhancing the comfort and interactivity of wearable devices by combining multi-color displays with flexible substrates. Such technologies offer a more energy-efficient and adaptable solution for the next generation of smart wearables.

6.2 Real-Time Monitoring of Human Health

The electrochromic material is formed by the combination of polyaniline and rare earth oxides (La2O3 and CeO2). Regarding whether it is possible to conduct health monitoring by monitoring the coloration of human body voltage changes in real time to report the changes in internal potential of the human body under different conditions. In Dai's (2023) study, the f-La_2O_3/PANI composites demonstrated faster response and better cycling stability than pure PANI. The electrochromic performance of the composite was optimal when the lanthanum-amine ratio was 1:3.5, with a coloring efficiency of 22.81 $cm^2 \cdot C^{-1}$ and fading and coloring response times of 1.29 seconds and 1.33 seconds, respectively. At a wavelength of 570 nm, the film reversibly changed between emerald green, dark green, and reddish-brown, while the f-CeO_2/PANI composite showed reversibly changing between emerald green, dark green, and reddish-brown. These composites all showed good color change and electrochemical performance during the electrochromic process. These properties give them great potential for electrochromic applications in human wearable devices.

7 SUPERCAPACITORS

7.1 Excellent Innovation in Electrode Materials

As industrialization progresses, the problem of energy consumption needs to be addressed. Traditional fossil fuels cause greenhouse effects and air pollution, and the development of clean energy is an inevitable trend. Supercapacitors, with their high power density and long cycle life, are an important part of energy storage, especially widely used in new energy equipment and defense equipment. Metal oxides, due to their high theoretical specific capacity and abundant natural resources, have attracted much attention as electrode materials for supercapacitors. Zhang Zhichao studied vanadium-cobalt bimetallic oxide ($VCoO_x$) by hydrothermal synthesis, and by controlling variables such as reactant concentration, reaction temperature, and time, samples of vanadium-cobalt bimetallic oxide with different micromorphic morphology were synthesized. These samples demonstrated excellent capacitance performance and cycling stability in electrochemical tests, and they successfully synthesized novel star-shaped and spheroidal Co3O4, expanding the variety of microstructure morphology of metal oxide materials and providing a reference for the innovative design of supercapacitor electrode materials (Zhang, 2024).

7.2 Fiber Supercapacitors

In recent years, the function of ECDs has expanded from a single electrochromic function to energy storage, resulting in electrochromic supercapacitors (ECSs), devices that can not only alter their optical properties but also store energy. WO_3/TiO_2 nanowire fibers can be woven into fabrics that not only store energy at a density of 15 Wh/kg, but also change color with the state of charge. Keon-Woo Kim et al. successfully fabricated mesoporous WO_3 electrochromic supercapacitors using polystyrene-polyoxyethylene (PS19k-b-PEO6.5k) and WCl_6 as raw materials through evaporation-induced self-assembly (EISA) technology. It has fast color-changing speed, high optical modulation, and excellent energy storage performance (Kim et al., 2020). As a result, metal oxide materials, due to their diverse structures and compositions, exhibit high specific surface area, excellent optical and electrochemical performance, enabling rapid ion transport and intercalation/deintercalation, and thus have advantages such as fast response, high capacitance, and good cycling stability in electrochromic supercapacitors and supercapacitors. It has driven the development of high-performance energy storage and display-integrated devices.

8 CHALLENGES AND EXPECTATIONS

Jia et al. (2023) mentioned that electrochromic metal oxides are costly to produce on a large scale because of their complex preparation process, which involves high-precision equipment and expensive raw materials. And even though they have more stable properties compared to organic materials, their stability in extreme conditions is still insufficient; especially in extreme conditions such as high temperature and high humidity, their performance may still gradually decline. Jia et al. (2023) also mentioned that integrating electrochromic functions with other functions (such as energy storage, sensing) into a single device requires addressing complex issues such as material compatibility, structural design, and performance optimization. Therefore, achieving multi-functional integration is complex and difficult. In Peng et al. 's (2025) study, metal oxide materials (such as WO_3, etc.) still have performance bottlenecks such as long response time, insufficient cycling stability, and limited optical modulation amplitude in high-resolution displays, which limit their application potential in high-resolution dynamic displays.

In future studies, green synthesis processes such as hydrothermal and sol-gel, which are low-cost and highly compatible, can be developed to reduce material preparation costs and improve process compatibility. And further explore new heterojunctions and porous structure designs, continue to design porous structures or heterojunctions, such as the MXene/WO_3 microcavity structure designed by Wang et al. (2025), and further improve ion transport efficiency and optical contrast. We can also deepen multifunctional integration research to promote the integration of electrochromic materials with energy storage, sensing, and self-powered systems, and develop multifunctional devices like electrochromic supercapacitors. Electrochromic metal oxide materials have the potential to achieve greater breakthroughs in green energy and smart interaction through interdisciplinary collaboration and technological innovation.

9 CONCLUSIONS

This paper systematically reviews the core advantages of metal oxide electrochromic materials in optical control, environmental stability, and preparation processes, and focuses on their innovative applications in energy-saving Windows, high-resolution displays, flexible electronics, and multifunctional energy storage devices. The study shows that through nanostructure design (such as MXene/WO_3 Fabry-Perrot microcavities) and lithography technology innovation (line width <4 μm), the optical modulation capabilities of metal oxide materials in the visible and near-infrared bands have been significantly enhanced (ΔT over 75%). It also has ultrafast response (coloring time <1 second) and long cycle life (>1000 times). In the field of flexible devices, the combination of MXene-based composites and self-healing technology (electro-optical synergistic ion release) enables the multifunctional integration of mechanical deformation and color change, providing new ideas for smart wearable devices. In addition, the development of dual-function electrochromic supercapacitors (such as WO_3/TiO_2 fibers) has promoted the synergistic development of energy storage and dynamic light regulation.

The development of electrochromic metal oxides still faces problems such as complex preparation processes, high costs, performance degradation in extreme environments, difficulties in multi-functional integration, long response times, and insufficient cycling stability in high-resolution displays. In the future, the development of green synthesis processes, the design of new heterojunctions and porous structures, and the deepening of multifunctional integration research are expected to enhance their performance and expand their application areas. And cross-disciplinary collaboration and technological innovation will drive greater breakthroughs in electrochromic metal oxides in green energy and smart interaction.

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