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REVIEW

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Color-changing coatings: The science and future of thermochromic and photochromic materials

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ABSTRACT

Color-changing coatings represent a promising frontier in advanced materials for dynamic and adaptive applications. This review explores the science and future of thermochromic and photochromic materials, focusing on their fundamental mechanisms, innovative fabrication techniques, and emerging applications. Thermochromic systems, which alter color in response to temperature fluctuations, and photochromic coatings, which change rapidly under UV or visible light, demonstrate reversible transitions with response times ranging from sub-second to several seconds. Recent advances in nano structuring and composite formulations have led to significant improvements in performance metrics, such as tuning transition temperatures (for example, VO_2-based coatings can be adjusted near 68°C) and achieving higher color contrast and cycling durability in spiropyran derivatives. Despite these breakthroughs, challenges remain regarding long-term durability, cost efficiency, and scalability for widespread use. Future prospects include developing multi-stimuli responsive systems and integrating smart digital controls to enhance functionality in applications like smart windows, wearable sensors, and adaptive displays. Overall, this review clearly outlines the state-of-the-art and future directions in dynamic color-changing coatings, paving the way for further innovation.

KEYWORDS

Color-changing coatings; Thermochromism; Photochromic coatings; Thermochromic materials

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Introduction

In recent years, the need for dynamic coatings has increased as industries look for innovative solutions for smart windows, adaptive displays, advanced sensors, and improved security systems. Color-changing coatings, which react to environmental stimuli, are becoming essential elements in these applications because of their potential to blend aesthetic attractiveness with functional advantages such as energy efficiency and environmental responsiveness. Their dynamic characteristics enable them to adjust light transmission and reflectivity, thus aiding in thermal management in buildings and enhancing visibility in display technologies [1].

Historically, the creation of color-changing coatings started with early thermochromic systems that depended on leuco dyes and liquid crystals. These systems displayed reversible color shifts when exposed to temperature changes but were frequently constrained by limited operating ranges and problems with durability. As research advanced, the area broadened to encompass photochromic materials, which experience rapid and reversible changes when subjected to ultraviolet or visible light. Contemporary photochromic compounds, such as spiropyrans and diarylethenes, have markedly enhanced response times and long-term cycling stability, allowing them to be suitable for a wider array of applications. These developments have led to coatings that not only change color but also retain reliable performance over thousands of cycles [2].

This review article centers on the science underlying color-changing coatings, highlighting both thermochromic and photochromic systems. It will scrutinize the fundamental mechanisms of color change, trace the progression from traditional materials to advanced compounds, and evaluate cutting-edge fabrication techniques that improve performance and durability. Additionally, the review will address emerging applications, pinpoint current challenges like environmental degradation and cost-effectiveness, and suggest future research paths focused on creating multi-stimuli responsive systems connected with smart digital controls by thoroughly investigating these subjects, the article seeks to impart valuable knowledge regarding the development and application of next-generation color-changing coatings [3].

Fundamentals of Color-Changing Coatings

Color-changing coatings are cutting-edge materials that display reversible color shifts in reaction to external stimuli, mainly temperature and light. The two main mechanisms driving these dynamic systems are thermochromism and photochromism, each functioning on unique principles while providing complementary features in smart material uses [2].

Thermochromism is defined by a reversible alteration in color initiated by changes in temperature. Fundamentally, thermochromic behavior results from a modification in the molecular structure or phase of the material, which changes its light absorption characteristics. A frequent example includes leuco dyes, which generally experience a color shift within a specific temperature range of 25–35°C. In these systems, the leuco dye remains in a colorless or lightly tinted state at lower

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temperatures and transitions to a distinctly colored state as the temperature increases [4]. Thermochromic liquid crystals serve as another illustration; they display vibrant, iridescent color changes as temperature varies due to alterations in their molecular alignment. The precise regulation of transition temperatures renders thermochromic materials appealing for uses such as temperature indicators, smart packaging, and thermal sensors [5].

Photochromism, conversely, entails a reversible color shift triggered by exposure to ultraviolet (UV) or visible light. This mechanism generally works through molecular isomerization, where light absorption causes a structural transformation in the molecules. An extensively investigated example is the spiropyran molecule, which changes to its merocyanine form when exposed to UV light, resulting in an observable color change. This change is fast, usually happening in less than a second, with the reverse reaction taking between one to three minutes under normal conditions. Photochromic materials find great applications in areas like adaptive lenses, smart windows, and security inks, where quick response times and reversible behavior are crucial [6]. Table 1, demonstrates that spiropyran-based compounds achieve quick color transitions in under one second with remarkable reversibility and long cycle life, making them suitable for uses such as smart lenses and adaptive displays.

Material/System	Mechanism	Response Time	Reversibility	Cycle Life	Typical Application
Spiropyran-Based Compounds	UV-induced isomerization	<1 second	High	>10,000 cycles	Lenses, smart windows
Diarylethene-Based Compounds	Ring-opening/closing mechanism	~0.5–1 second	Very High	>10,000 cycles	Optical data storage, security inks
Hybrid Nanocomposites	Combined photochromic agents	~0.5 second	High	>15,000 cycles	Adaptive displays, sensors

Several key parameters influence the performance of both thermochromic and photochromic systems. Response time is an essential metric, especially for applications that require quick feedback, such as in displays or optical sensors. Color contrast—the extent of difference between the colored and uncolored states—is also crucial for ensuring clear visibility of the transition. Durability, which includes resistance to environmental degradation (e. g., UV exposure, thermal cycling) and fatigue resistance over numerous cycles, is necessary to sustain long-term functionality. While reversible systems are engineered to cycle repeatedly between states without considerable performance loss, irreversible systems—typically employed in security or one-time indicators—experience a permanent change post-activation. Reversible systems present the benefit of repeated usage and dynamic responsiveness, while irreversible systems can offer a distinct record of exposure to specific conditions [7].

In summary, thermochromic and photochromic materials form the basic mechanisms for color-changing coatings. Thermochromic systems provide controlled, temperature-induced transitions that are perfect for thermal sensing and energy management applications, whereas photochromic materials produce swift, light-induced color shifts that are ideal for adaptive optics and security applications [8]. Ongoing research persists in optimizing these systems, aiming to improve response times, color contrast, and durability to satisfy the increasing demands for smart, multi-functional coatings in advanced technological applications [9].

Materials advances

Early color-changing coatings mainly depended on leuco dye systems, which showcased the initial examples of thermochromic behavior. However, these early systems were constrained by a limited temperature range—usually functioning effectively only between 25–35°C—and experienced fading over time, which hindered their long-term performance and practical use. Such constraints led to extensive investigations into advanced materials capable of overcoming these obstacles and broadening the operational range and longevity of color-changing coatings [10].

Recent progress in thermochromic materials has positioned vanadium dioxide (VO_2) at the forefront. VO_2 demonstrates a well-established insulator-to-metal transition at around 68°C, which is accompanied by a noticeable color change. Significantly, the transition temperature of VO_2 can be adjusted through doping; for instance, tungsten-doping has been found to reduce the transition temperature to about 40°C, expanding the array of possible applications. Furthermore, the addition of nanostructured polymer blends with thermochromic characteristics has greatly improved cycling stability, ensuring that the materials retain their performance over thousands of thermal cycles. These advancements tackle both the operational range and durability problems that affected earlier systems [9,11]. As indicated in Table 2, nanostructured polymer blends not only provide tunable transition temperatures but also display improved response times (0.5–1.0 seconds) and durability that exceeds 2,000 cycles compared to conventional leuco dye systems.

Material/System	Transition Temperature (°C)	Color Change Range	Response Time	Cycle Durability
Leuco Dye-Based Systems	25–35	Subtle (limited contrast)	1–2 seconds	~500 cycles
VO_2 (Pure)	~68	Moderate (gray/clear)	1–2 seconds	~1,000 cycles
Tungsten-Doped VO_2	~40	Enhanced contrast	0.8–1.5 seconds	~1,200 cycles
Nanostructured Polymer Blends	Variable (tunable)	High (vivid colors)	0.5–1.0 seconds	>2,000 cycles

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In the field of photochromic materials, recent advancements have concentrated on spiropyran-derived compounds, which provide quick response times—often in under one second—and high reversibility, rendering them particularly appealing for uses necessitating swift, dynamic color alterations. Diarylethenes have also emerged as a strong alternative due to their outstanding fatigue resistance; these substances can withstand more than 10,000 switching cycles without significant degradation, thus ensuring consistent performance over long durations. For example, commercially available photochromic lenses on the market can alter light transmittance from 20% to 60–70% when subjected to sunlight, demonstrating their practical effectiveness in real-world scenarios [8,12].

Comparative information clearly highlights the benefits of these advanced materials. Nanostructured coatings, for instance, have shown response times as quick as 0.5 seconds, along with improved durability in comparison to their conventional equivalents. These advancements in response time and stability are vital for applications in smart windows, adaptive displays, and wearable sensors, where prompt and steady color transitions are crucial for functionality and user experience. Current research is now investigating multi-layered structures and hybrid composites that combine both thermochromic and photochromic responses within a single coating [5,7]. These multi-stimuli responsive systems aim to provide enhanced functionality by reacting to both temperature and light changes at the same time. Such integration holds potential for creating next-generation smart materials that can be precisely tailored for specific applications, ranging from energy-efficient building materials to advanced security features [13].

The Progress in the field of material science has resulted in notable enhancements in color-changing coatings. By evolving from early leuco dye systems to sophisticated thermochromic and photochromic materials—supported by nano structuring and hybrid composites—researchers are surmounting prior limitations and setting the stage for highly responsive, durable, and versatile coatings with extensive application potential [14].

Fabrication Techniques and Processing

Fabrication methods and processing are crucial in determining the performance of color-changing coatings, as they directly impact their responsiveness, longevity, and overall efficacy. Different deposition techniques are utilized to produce these coatings, each presenting distinct advantages and challenges. For example, spray coating is commonly favored due to its straightforward nature and cost efficiency, permitting quick application over extensive areas. Nevertheless, managing film consistency and thickness can be difficult with this technique. Conversely, sol–gel processes provide excellent control over microstructure by allowing the formation of uniform films at comparatively low temperatures. This approach supports the addition of functional additives and the precise adjustment of optical characteristics. Moreover, inkjet printing has emerged as a flexible method, particularly well-suited for creating patterns and the application of intricate multilayered structures, essential for realizing targeted color-changing effects [15,16].
Microstructural regulation is vital in influencing the optical performance of color-changing coatings. Factors such as particle size, film thickness, and surface roughness considerably impact the efficiency of color transitions and overall response times. Smaller particles can improve the coating's responsiveness by increasing surface area and ensuring more uniform engagement with stimuli. Accurate control of film thickness is similarly crucial, as it determines the degree of color change and the coating's durability [12,17]. Additionally, surface roughness can either enhance or reduce optical effects depending on the specific application; for instance, a smoother surface may be necessary for applications requiring high clarity displays, whereas a textured surface might be beneficial for diffusing light in smart window technologies [16,17].

Scalability remains a significant hurdle when moving from laboratory-scale deposition techniques to industrial production. Attaining uniformity and stability over extensive areas requires advanced process control and monitoring systems. Fluctuations in environmental conditions, substrate characteristics, and deposition parameters can result in inconsistencies in film attributes, ultimately impacting performance. Addressing these issues demands not only technological advancements in deposition techniques but also progress in real-time quality control and process optimization. In conclusion, while existing fabrication methods such as spray coating, sol–gel processes, and inkjet printing have allowed major progress in color-changing coatings, ongoing research into microstructural control and scalable processing is crucial for their effective commercialization and widespread application [18,19].

Applications of Color-Changing Coatings

Color-changing coatings possess a broad spectrum of applications that exploit their distinctive capacity to respond dynamically to external stimuli, providing both functional and aesthetic advantages. In smart windows and building exteriors, these coatings facilitate energy conservation through efficient solar heat management. By adjusting their optical characteristics in real time, such coatings can regulate the volume of solar radiation entering a building, decreasing cooling demands in the summer and improving insulation during the winter, which in turn reduces energy usage and utility expenses. This adaptive capability is especially beneficial in contemporary architectural designs aimed at sustainability and eco-friendly building practices [15,20].

In optical displays and sensors, the quick response of photochromic materials—often changing in under a second—promotes the creation of adaptive displays featuring rapid color modulation. These displays can modify their brightness and contrast instantaneously, increasing visibility in varying light conditions and enabling creative interactive uses. Moreover, these coatings act as sensitive elements in optical sensors, where accurate color transformations can signal environmental changes or identify chemical substances [21].

The security and anti-counterfeiting industry similarly gains from the use of color-changing coatings. Distinct, dynamic color patterns generated by these materials provide a strong approach for product verification, making forgery more challenging and safeguarding brand reputation. The unique

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optical identities offered by thermochromic and photochromic components function as a dependable verification mechanism in currency, documents, and luxury items [22].

Lastly, wearable technologies, including mood rings and temperature monitors, take advantage of the rapid response and reversible properties of these coatings. Embedded in fashion accessories or health-tracking devices, they offer immediate visual feedback on environmental factors or physiological alterations, blending functionality with personal style. Collectively, these varied applications highlight the adaptability and transformative capacity of color-changing coatings in enhancing both technology and daily life. [19,23].

Challenges and Future Directions

Despite the encouraging progress in color-changing coatings, numerous challenges persist that need to be addressed for their broad commercial utilization. One significant constraint is the longevity of these coatings under extended UV exposure and environmental damage. Ongoing exposure to sunlight, moisture, and variable weather conditions can result in decreased switching speed, color fading, and an overall decline in performance. This deterioration is especially concerning for outdoor uses such as smart windows and building facades, where long-term durability is crucial [24].

Simultaneously, research opportunities are plentiful to improve the fundamental characteristics of these materials. Initiatives are in progress to enhance switching speeds, which are vital for applications that require quick responses, such as adaptive displays and sensors [13,24]. Moreover, the creation of multi-responsive coatings that can respond not only to temperature or light but also to additional environmental stimuli is an exciting area of investigation. Such improvements could vastly expand the functionality and applicability of color-changing coatings [22,25].

Combining these coatings with intelligent systems presents another promising avenue. Incorporating IoT sensors and digital control technologies can facilitate real-time monitoring and adaptive modifications, maximizing performance in relation to surrounding conditions. This integration of material science and digital technology could open new opportunities in energy management, security, and interactive interfaces [26].
Lastly, cost and scalability are still major obstacles. The financial feasibility of manufacturing these advanced coatings on a large scale depends on further enhancing production methods and lowering manufacturing expenses. Tackling these issues through ongoing research and process innovation is vital to realize the complete potential of color-changing coatings in various commercial sectors [27].

Conclusions

In conclusion, the development of color-changing coatings has resulted in significant advancements, evolving from primitive leuco dye systems to sophisticated thermochromic and photochromic materials that provide quick, reversible, and dynamic responses. Breakthroughs such as tungsten-doped VO_2, nanostructured polymer blends, spiropyran-based compounds, and diarylethenes have not only enhanced switching speeds and durability but also broadened the functional advantages of these coatings in applications like smart windows, adaptive displays, security uses, and wearable technology. These developments offer remarkable comparative advantages, including improved energy efficiency, quicker reaction times, and increased cycling stability, thereby expanding the variety of potential applications.
Looking ahead, upcoming research needs to tackle the remaining issues of long-term durability in extreme environmental conditions and the economic challenges of increasing production capacity. Focusing on the creation of multi-responsive coatings that work in conjunction with IoT sensors and digital control systems will be essential. These interdisciplinary initiatives are expected to maximize performance, lower costs, and ultimately facilitate the advancement of next-generation color-changing coatings with a more extensive commercial and technological influence.

Disclosure statement

No potential conflict of interest was reported by the authors.

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