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Structural color from basic principles to emerging applications

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Wenhao Wang and colleagues summarized the latest advancements in structural color research in *Opto-Electronic Science*. Their review explored the fundamental principles and fabrication methods of structural colors for photonic applications, including anti-counterfeiting, displays, sensors, and printing, along with their practical limitations. Recently, structural colors have received growing interest due to their advantages, including physical and chemical robustness, eco-friendliness, tunability, and high-resolution color. With the rapid advancement of nanofabrication and design methodologies, there is a growing need to systematically review recent progress in structural colors and provide future perspectives. This review provides insights into the structural color research and highlights critical challenges to be overcome.

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Color shapes our perception of the world, yet traditional pigments and dyes have long dictated its application. Structural colors, created by the interaction between light and periodic nano- or microstructures, present a promising alternative. Inspired by nature, they offer advantages such as physical and chemical robustness, eco-friendliness, tunability, and high-resolution color. Therefore, many recent studies focused on implementing structural colors such as thin film layers, diffraction grating, photonic crystal (PC), and dielectric or metallic metasurface[1–5]. Furthermore, recent advances in nanofabrication enable novel platforms to enhance the design degree of freedom for structural color[6–9]. In this context, there has been a growing need to systematically review fabrication methods and design strategies to help researchers choose the most suitable approach based on their needs.

In a recent work in *Opto-Electronic Science*[10], Wenhao Wang and colleagues summarized the latest advancements in structural color research, discussing fabrication techniques, fundamental mechanisms, and emerging applications in areas like anti-counterfeiting, displays, sensors, and printing. The review categorized fabrication methods into top-down approaches, which involve elaborate nanopatterning, and bottom-up approaches, which include self-assembly and thin-film deposition. Top-down approaches offer high resolution and precise control over nanostructures but come with high fabrication costs. In contrast, bottom-up approaches are more cost-effective and scalable for large-area fabrication, though they have limitations in structural precision. Wang and colleagues systematically summarized the latest research on structural color fabrication by categorizing different methods in a comprehensive table, highlighting their fabrication strategies, advantages, and functionalities, helping readers select the most suitable approach for

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their specific applications.

The review introduced the five fundamental principles of structure color, including 1D PC, Fabry-Perot (F-P) cavity, 2D and 3D colloidal crystal, and metasurface. 1D PCs can be fabricated without expensive lithography-based fabrication and instead be realized through thin-film deposition, making them more cost-effective. Structural colors in 1D PCs arise from the selective reflection of specific wavelengths, which is induced by photonic bandgaps formed through the interference of light between film layers. The F-P cavity has a similar structure to a 1D PC but is more compact as it requires only three layers. Its asymmetric design, consisting of a thin top metal layer and a thick bottom mirror layer, forms a cavity that confines light within the dielectric layer. This confinement results in the formation of absorption peaks or reflection dips, which generate structural colors. 2D and 3D PCs generally operate based on interference theory from self-assembled colloidal crystals. Since they are self-assembly-based, they offer advantages in terms of low cost and large-scale fabrication. Metasurfaces, on the other hand, consist of artificially engineered nanostructures that can be optimized at the unit-structure level to achieve vivid, high-resolution colors through impedance matching. However, their application is limited due to the high-cost nanofabrication equipment required. To provide a clear guideline on selecting the appropriate mechanism based on its strengths and limitations, the review presents a comprehensive table summarizing the key advantages, disadvantages, and critical parameters of each mechanism.

Based on the introduced fabrication methods and fundamental mechanisms, structural colors have been actively explored for various applications, including anti-counterfeiting, displays, sensors, and printing. Wang and colleagues organized recent advancements in these four application areas, highlighting their potential and limitations. In anti-counterfeiting and display applications, key challenges include expanding the number of channels and broadening the color range. To address these issues, researchers have developed multi-channel platforms that respond to changes in incident angle or polarization state and stimuli-responsive platforms based on hydrogels, liquid crystals, and ITO[11,12]. In sensors, structural colors have been applied to detect drugs, temperature, humidity, and pH. However, most of these rely on changes in water content, limiting their long-term usability. Therefore, not only long-term stability but also high resistivity, environmental resistance, and multi-responsiveness are crucial challenges that need to be addressed. In printing, large-scale fabrication, the ability to create complex and fine patterns, a wide color range, and customized color rendering are essential factors. This review introduces various printing methods, including recent advances in two-photon lithography (TPL)-based printing, which enables the fabrication of intricate 3D structures.

In summary, this review provides a comprehensive guide by summarizing fabrication methods and fundamental mechanisms, helping readers select appropriate strategies. Additionally, it offers insights into recent application trends, providing a valuable perspective on the field of structural colors. This work serves as a useful reference for understanding the current state of structural color research and identifying the key challenges that must be addressed. One major trade-off in the field is the high fabrication cost of nanopattern-based structural colors, despite their ability to achieve ultra-high-resolution color. Overcoming this limitation could lead to a breakthrough in commercialization. Recently, wafer-scale nanoimprint lithography (NIL), along with roll-to-plate (R2P) and roll-to-roll (R2R) NIL techniques, have gained significant attention[13–15]. Integrating these methods into structural color fabrication could enable large-scale, cost-effective manufacturing, addressing a key challenge in the field.

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