Nanostructure Contribution to the Coloration of Butterfly Wings

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Natural colors have always attracted the eyes of human being for a long time. The original scientific study of brilliant feathers of peacocks was probably first carried out by Hooke and Newton in the 17th century through observation using optical microscopes. Since the establishment of electromagnetic wave theory and experiments by Maxwell and Hertz in the late 19th century, the fundamental properties of light such as reflection, refraction, scattering, interference and diffraction could be examined quantitatively thereafter, and the studies on natural colors developed quite rapidly. Natural colors can be generated in three distinct ways: pigments, elements, and surface structure [1, 2]. Pigments are responsible for colors in leaves and animal skins; elements are responsible for colors in minerals and rocks; and, surface structures are responsible for colors in animals such as certain crabs, beetles, and butterflies. Among these three color causing mechanisms, the surface structure-induced coloring has attracted extensive attention in recent years because of its chemical-addictive-free applications in many industrial fields such as electronics, paintings, automobiles, cosmetics, display technologies, and textiles.

For this purpose, we selected the Morpho Butterfly (Morpho didius) to study the correlation between its surface structure and its beautiful coloration. The Morpho Butterfly is famous for its blue dorsal side of its wings which are used to attract mates and fend off predators. The ventral side of the wing is brown with Ocelli spots, which are used as camouflage against predators. The average lifespan of a Morpho Butterfly is about four months with about one month in the adult stage. The Morpho Butterfly was acquired from an insect vendor, Delia Designs, TX. After the wings were dried in desiccators for four hours, the right bottom section of blue dorsal side of the wing and its cross-section prepared using ultramicrotome were examined in detail using an ESEM operated at 5 keV. In addition, the wing composition was determined by an Oxford Energy Dispersed X-ray system (EDX) attached to the ESEM. Microstructures of the Morpho Butterfly wings were additionally observed more in depth with a 200kV TEM in order to confirm the structure observed in ESEM. White Cabbage Butterfly was also examined using ESEM and compared in detail.

Through electron microscopy examining the surface structures of the Morpho Butterfly on both micro and nanoscales, the specific cause of its iridescence is determined with a focus on the light-nanostructure interactions. It was found that the air-cuticle multilayering structure caused the coloration of metallic blue color on the dorsal side. Further work was also extended to study the brown ventral side of Morpho Butterfly and White Cabbage Butterfly (Pieris rapae). The images on the left side of Fig. 1 give the outlook of both the blue dorsal side and the brown ventral side of the Morpho Butterfly and the White Cabbage Butterfly wings. All three sides of the butterfly wings have ordered hierarchical structures at both the micrometer and nanometer scales. At low magnification, the wings consist of overlapping scales of different shapes and sizes [Figs. 1, (a, c, e)]. At higher magnification, the wings have lamellae running vertically (orange arrows) and cross ribbings (blue arrows) running perpendicular to the lamellae [Figs.1 (b, d, f)]. The spacings between the lamellae and cross ribbings differ for each side. Measurements for these spacings and thicknesses were made. In addition, nanospherical particles with an average radius of 100 nm were found grouped randomly on the surface structure of the White Cabbage Butterfly. This feature acts as a scattering agent for both short and long wavelength reflectance, giving the cabbage butterfly its white color. Interesting features were found in the blue dorsal side of Morpho Butterfly. The side-view and cross-section
view of lamellae structures are shown in Figs. 2(a) and (b), respectively. The lamellae were observed to have overlapping ridges. This cuticle layering was then examined at different angles with both the SEM and TEM. Measurements of the ridges on the lamellae show (a) the distance between the steps of the ridges seen from the top view averaged to be about 1.15 μm. The ridges seen from the side-view were angled at about 9° from the surface. Fig. 2(b) depicts the tree-like structure viewed from the cross-section which forms a cuticle-air multilayering with Cuticle thicknesses averaged to be about 113 nm, and the air gaps (or voids) averaged to be about 74 nm. With detailed calculation using Bragg’s interference theory [3], we conclude that the blue color of the wing is caused by a unique hierarchical, air-cuticle multi-layering structure that causes a constructive interference of ~470 nm. This has been confirmed with a Raman microscopy experiment. Other nanostructure related surface property such as hydrophobicity, chemical etching pattern has also been studied.

Reference:

Figure 1: Three butterfly wings and corresponding ESEM images of surface lamellae and cross ribbings for the regions as pointed by arrows, (a,b) dorsal (blue) side of Morpho butterfly; (c,d) ventral (brown) side of Morpho butterfly; (e,f) Pieris rapae.

Figure 2: Dorsal side of Morpho didius (a) SEM image of oblique view of cracked lamellae; (b) SEM image of cross sectional view of lamellae. [Scale bar: 1 μm for (a) and 0.2 μm for (b)]