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Living Light: Uniting biology and photonics – A memorial meeting in honour of Prof Jean-Pol Vigneron

Multiscale replication of iridescent butterfly wings

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Abstract

Natural photonic structures have been extensively studied and have shown their interest as a source of inspiration for new bio-inspired devices in many areas. After these initial studies and characterization phases, we have now to reproduce these structures, mainly in inorganic materials, to exacerbate interesting effects or generate new ones. If we want to preserve the best of their multi-scale and more or less ordered structures, producing a molding seems more appropriate. Such prints can be achieved by physical or chemical means, the latter being *a priori* particularly suitable for three-dimensional structures.

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Keywords: molding ; Morpho ; PVD ; sol-gel ; photonic structure

1. Introduction

To manage the physical and chemical exchanges between the outside world and living organisms, and enable them to cope with the various constraints that apply to them, evolution has led to the development of many different structures at any scales [1, 2]. The general characteristics of these natural structures are: (a) Multifunctionality. Structures systematically assume several vital functions for the body and are optimized on average for all of these functions. (b) Unlike our artificial devices, natural structures use only very few elements of the periodic table. (c) These two characteristics, doing more with less, impose a multi-scaled complex structure, with a controlled disorder

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(Fig.1) [3-8]. Despite progresses recently reported [9], these latter characteristics are generally difficult to artificially reproduce using conventional techniques of nano-structuring. In the case of butterfly wings, various chemical and physical routes have been thus investigated for replicating natural architectures including physical vapor deposition (PVD), chemical vapor deposition, atomic layer deposition, and chemical solution deposition (CSD) [10-13]. These approaches give rise either to a thin positive replica, natural structures serving as scaffolds, or a negative one, natural structures being used as molds. At this stage, two general remarks concerning replica and deposition could be done: (a) Replica are rather brittle and present usually a limited size after biotemplate removal (a few tens of microns) which limit their further handling, use, and integration into more complex devices. (b) A given deposition technique could be more or less adapted to a natural structure depending on its periodicity dimension (1D, 2D, 3D). Indeed, physical deposition methods, rather directional are well suited to two-dimensional but could be less efficient for most of the three dimensional structures, unlike chemical solution deposition methods, which allow a good infiltration of the 3D structures. In this article, we compare two deposition techniques (PVD and CSD) to produce thick negative replica of multi-scale and three-dimensional structures of iridescent butterfly wings.

2. Butterfly wings replication

The two butterflies that we used as biotemplate are males of the Morphidae family: *Morpho rhetenor* (Fig. 1) and *Morpho menelaus*. The wing are covered by different types of scales, cover and ground photonic scales (approximately 100 µm x 50 µm), each scale being itself covered by a grating of ridges (1µm apart). The ridges are composed of a stack of lamellae (50 nm thick) which acts as a multilayered air – chitin film. Optical thicknesses of the layers are such that only blue waves interfere constructively [4, 7, 14].

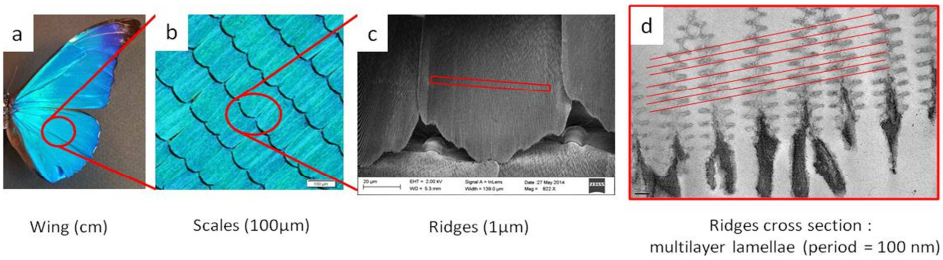

Fig. 1. The different scales used to observe butterfly wings (*M. rhetenor* male) and their units of measure: (a) Dorsal side of the wing; (b) Organization of the scales (optical microscopy); (c) SEM view of a photonic scale; (d) TEM view of a transversal cut in a photonic scale. [7, 14]

Physical vapor deposition of SiO_2 was prepared by RF sputtering using a diode module having a power supply operating at 13.5 MHz, a disk-shaped electrode of 13 cm in diameter and a SiO_2 target to substrate distance of 4 cm. The base pressure of the vacuum chamber is 10^{-6} Torr and the sputtering takes place in an argon atmosphere at a pressure of 10 mTorr and at a temperature of 100°C. It is worth mentioning that the multiscale structure of butterfly wings is preserved in similar experimental conditions (blank test), *i.e.* low pressure and 200°C, since slight color variations of the wing are observed. This observation is confirmed by TGA analysis performed on butterfly wings which displays not significant loss below 200°C. The silica deposited layer on the wing of a *Morpho rhetenor* is about 2 microns thick after 13h.

Chemical solution deposition used in this study combines sol-gel chemistry, solution evaporation process and dip-coating. This method consists in the deposition of a solution of precursors containing titanium isopropoxide, acetylacetone (acac) and ethanol (EtOH) as solvent (molar ratio: 1 Ti : 2 acac : 10 EtOH). The titania-based film was deposited at withdrawal speed of 0.68 $cm.s^{-1}$ in a relatively dry atmosphere (relative humidity RH = 15 %). In order to promote controlled hydrolysis-condensation reactions, samples were next aging 24 hours at 35°C and RH = 75%. The titania-based layer coated on the wing of a *Morpho menelaus* is about 2 microns thick.

SEM images were obtained with a SEM Hitachi S-3400N and a Zeiss Neon40 ESB CrossBeam SEM-FEG with FIB. TGA experiments were performed with a TGA Netzsch STA 409 PC. Ellipsometry measurements were done with M-2000U Woollam spectroscopic ellipsometer.