A novel technique for making highly efficient biomimetic devices

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The conformal-evaporated-film-by-rotation technique generates synthetic, faithful replicas of biological structures, with broad potential application.

Living organisms provide inspiration for innovations in many different fields and for entirely different reasons. Energy is stored in a chemical form by plants with almost 100% efficiency. Animal muscle is an efficient mechanical motor capable of an exquisite degree of control. Transmission of information in the nervous system is more complex than in the largest telephone exchanges. And the problem-solving capabilities of a human brain greatly exceed those of the most powerful supercomputers.1 In this vein, biological species furnish numerous examples of structures exhibiting multifunctional properties. For example, insect bodies contain photonic micro- and nanostructures that create external coloration changes with viewing angle (iridescence) or appear metallic.

Biomimetics, in the broadest sense, is aimed at exploiting these natural structures and functionalities for use in technological applications. However, the mechanisms underlying the formation of biological structures are tremendously complex. This makes it extremely difficult, if not impossible, to imitate those mechanisms as a means of fabricating synthetic replicas. An alternative approach uses templates harvested from a particular species to provide a form when replicating a structure. Thus, bioreplication aims to take advantage of physical and spatial features of biological structures to develop novel devices with tailored functionalities. This could result in reliable and inexpensive processes for making complex nanostructures with unique sets of diverse functionalities, which in turn might have a significant impact on the manufacture of devices for use in fields ranging from medicine to security.

Figure 1. Scanning-electron microscope image of the replica of a biotemplate harvested from the eye of a tephritid fly (common fruit fly).

The exact replication of biotemplates by artificial methods is, in general, limited by the capabilities of currently available technology. In this respect, two major problems arise. First, there may be no technique available to grow high-fidelity replicas, particularly for nanoscale or curved biotemplates. Second, most physical or chemical processing methods will result in damage to or the destruction of the original biotemplate since these methods often require elevated temperatures or exposure to chemical agents and mechanical stress. Within this context, we have developed a novel technique, the conformal-evaporated-film-by-rotation (CEFR) technique, to fabricate high-fidelity replicas of biotemplates with micro- and nanoscale features distributed

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over planar and curved surfaces. In CEFR, the template is rotated rapidly while undergoing the oblique angle deposition technique for generating a thin film. The original template is then separated from the coating with a plasma ashing process.

The CEFR technique is particularly well suited for bioreplication as the temperatures involved during deposition are sufficiently low and the replication process occurs in a non-corrosive environment, thereby avoiding damage to the underlying biotemplate. The compound eyes of insects are attractive candidates for bioreplication as they present a desirable optical scheme for imaging with a very wide field of view.

Using the CEFR technique, we have successfully created a replica of the eye of a fruit fly (see Figure 1). There is neither a distortion of the original structure nor any observable new structure created by the replication technique. As the CEFR technique was implemented at low temperature, the spatial features of the eye were preserved during deposition. We have experimentally determined that a similar optical response in the visible and near-infrared frequency regimes is observed before and after replication, thereby indicating that the structure of the biotemplate was replicated with high fidelity, preserving the original optical functionality. As with the surface of the compound eye, the replica acts as a complex diffraction grating. These gratings, when arranged on a curved corneal area, reduce reflection of incident light compared to a planar and optically smooth surface, thus maximizing light transmission into the eye. The replicate device could serve to enhance light collection for solar energy collectors, optical communication systems or microcameras.

We have also used the CEFR technique to replicate the wing of a butterfly (see Figure 2). The butterfly wing has a photonic band-gap structure that provides its particular color as well as additional functionalities, including aerodynamics, light weight, mimicry, and camouflage. The replicated wing is composed of thousands of scales. These are intricately shaped with stratification, voids, and grooves of complex shapes that result in several optical effects, such as interference, scattering, and diffraction. Since the morphology of the butterfly wing makes it a very efficient diffuser of light, the replica could be used as an antireflection structure for increased photon trapping or as an optical diffuser.

The CEFR technique allows the use of insulating materials, metals, semiconductors, semimetals, polymers, and organic materials when making a replica. It is a simple, highly reproducible, and inexpensive process for fabricating complex nanostructures with biologically inspired functionalities. We have used the CEFR technique to successfully replicate biotemplates that could further the development of highly efficient photonic devices. For example, compound eye-based miniature cameras and optical sensors could be integrated into automobile engineering, credit cards, displays, and security and surveillance applications. Moreover, high-efficiency light-focusing/collating solar-cell covers and other energy-harvesting structures could be developed. Other potential applications include environmental sensing, high-speed motion detectors, and medical procedures that require cameras such as endoscopies and image-guided surgeries, as well as clinical treatments that can be controlled by implanted light-delivery devices. We are currently looking at the application of our technique to generate replicas with potential application in chemical sensors, biosensors, strain sensors, and light-emitting diodes for use in screens for laptops and cell phones, providing improved angular quality.

Figure 2. Chalcogenide replica of the butterfly wing created by the CEFR technique.

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