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Replication of fly eyes by the conformal-evaporated-film-by-rotation technique

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Abstract

We replicated a biological template, namely the eye of a fruit fly, at the micro- and nanoscales by implementing the conformal-evaporated-film-by-rotation (CEFR) technique, which allows the replication of even curved biotemplates. Chalcogenide glasses were used for replication due to their infrared optical properties, combined with good chemical and mechanical durability. Microscopy, together with optical characterization in the visible and near-infrared ranges, indicates high-fidelity replication of the original biotemplate. The CEFR technique could be useful for the development of highly efficient, biomimetic optical devices.

(Some figures in this article are in colour only in the electronic version)

The authors dedicate this paper to Professor R Messier on the occasion of his 65th birthday.

1. Introduction

Millennia of evolution have resulted in biological structures with very specific functionalities that are well adapted for survival. Mimicking of biological structures aims to take advantage of their spatial features for novel devices with desirable functionalities. Naturally, the exact replication of biological structures by artificial methods is, in general, limited by the capabilities of currently available techniques [1], and novel techniques are highly desirable.

Among biological structures of interest for replication, compound eyes are attractive candidates as they show a unique optical scheme for imaging, allowing such issues as wide field-of-view (FOV) detection [2]. Thus, the development of compound-eye-based miniature cameras and optical sensors would lead to their integration into tight spaces in automobile engineering, credit cards, displays, security and surveillance, and medical technology [3]. As artificial compound eyes have enormous potential for medicine, industry and security, biomimetic attempts have been made to duplicate their functionalities [4]. An alternative approach to replicate natural shapes is by using a template harvested from a particular species, and then converting it to an inorganic material. Replication of different biotemplates has been previously demonstrated by the atomic layer deposition technique [5, 6] and nanoimprint lithography [7].

The oblique angle deposition (OAD) technique has been recognized as a method capable of generating nanostructured thin films [8]. It is based on directing a vapor flux towards a substrate, with the trajectory of adatoms not parallel to the substrate normal. The arriving adatoms coalesce on the substrate to form nominally parallel columns, thereby endowing the resulting thin film with an intrinsically anisotropic morphology. This morphology and the corresponding physical properties can be tailored by altering the deposition conditions. Sequential substrate movements can be used to shape the columns, thereby modulating the physical response characteristics, which make the OAD films suitable for applications in many different fields [8]. Although this deposition technique has been previously used to replicate micro- and nanotemplates [9–11], no attempts have been reported using biotemplates.

Chalcogenide glasses are characterized by large values of the index of refraction within the visible and infrared spectral regimes. Furthermore, they are technologically important due to (i) their high infrared transmittance and (ii) the possibility

of modifying their optical bandgap and index of refraction by illumination [12]. These properties make them suitable for the development of passive and active infrared devices, especially optical components and sensors. Moreover, Ge-based chalcogenide glasses have been successfully deposited by OAD, thus adding extra functionality to their optical properties by tailoring morphology [13, 14] and, in turn, enabling new applications. Since the compound eyes of flies are very efficient collectors of light, their replicas could be used to fabricate solar cell covers and other energy-harvesting structures as well as lenses offering good spatial resolution. Through the use of infrared transparent chalcogenide glasses (transparent from 1 to about 20 μm), infrared microlenses and visible laser-hardened infrared sensors can also be envisioned. Additionally, application for photodiodes might be of interest, including horizon sensors used in satellite orientation systems and solar tracking systems for solar cells.

In this work, the successful replication of a biotemplate—the compound eye of a tephritid fly (common fruit fly)—by rapidly rotating it and implementing the OAD technique [15, 16] is demonstrated. We call this the conformal-evaporated-film-by-rotation (CEFR) technique. We show that the CEFR technique is capable of replicating the natural eye structure on the micron and nanoscales over a curved surface, at least in the case where an amorphous glass-forming material is used for the replication.

2. Experimental details

We used bulk chalcogenide glass with nominal composition $Ge_{28}Sb_{12}Ge_{60}$ for the deposition of amorphous GeSbSe thin films onto biotemplates using the CEFR technique. The GeSbSe was thermally evaporated using a current of 95 A with the vapor flux directed towards the substrate at an angle of 85° to the substrate normal, resulting in a coating of typical thickness in the range 0.5–1 μm. Other techniques are limited to the deposition of layers a few nanometers thick. During the deposition, the substrate holder was rotated at a constant speed.

Reflectance spectra in the 200–1700 nm wavelength range were taken by using a Perkin Elmer Lambda 950 UV/vis/NIR spectrophotometer. An integrating sphere was used to take scattering losses into account.

Scanning-electron microscopy (SEM) characterization was performed by the use of an FEI Quanta 200 ESEM. This system is capable of resolving 4 nm at 30 kV in high vacuum mode.

Plasma ashing was performed on the coated structure by the use of a Metroline M4L Plasma System to remove the original biotemplate. Thus, a replica is obtained after the coating is separated from the biotemplate.

3. Results and discussion

The compound eye of a fly is composed of integrated optical units called ommatidia which are spherically arranged following a hexagonal pattern along a curvilinear surface. Each ommatidium is composed of a facet lens, a (crystalline) cone, a set of photoreceptors and surrounding pigment cells [17]. Compound eyes provide inputs for the visual neuropiles, which process the light signals to detect motion, colors or patterns of interest. The numerous ommatidia of an insect eye collaborate to collect maximum optical information. In addition, the surface of an ommatidium is textured at the nanoscale. Accordingly, the biotemplate used in this work is both curved and decorated at the micro- and nanoscales. Figures 1(a) and (b) show two SEM images at different magnifications showing the structure of the eye of a fly.

Figure 2(a) clearly shows that the structure of the eye of a fly is replicated at the microscale by the GeSbSe coatings grown by the CEFR technique, i.e. there is neither a disturbance of the original structure nor an observable new structure created by the deposition process. As the CEFR technique was implemented at room temperature, the spatial features of the eye of the fly were preserved during deposition. Figure 2(b) provides a high-magnification image which shows that the CEFR technique allows the individual replication of each ommatidium. It is observed that the areas between neighboring ommatidia were not completely filled in with the evaporated material, but were conformally coated instead. The even more magnified image in figure 2(c) shows that even nanoscale features of the ommatidia were replicated by the CEFR technique.

Qualitative chemical analysis of the coated structure was performed by energy-dispersive x-ray (EDS) characterization to validate the deposition process. In figure 2(d), the EDS spectrum of the coated structure shows peaks associated with the three atomic components of the chalcogenide glass—namely, germanium, selenium and antimony. Additionally, strong carbon and oxygen peaks, associated with the organic composition of the eye of the fly, are present. Thus, the biotemplate was replicated in the glass thin film.

A plasma ashing process was used to separate the original biotemplate from the coating, thereby obtaining a replica of the biotemplate. Figure 2(e) shows an optical microscopy image of a replica alone, confirming that it is a self-standing structure.

The high fidelity of the replica made by the CEFR technique is due to substrate rotation at a high rate, typically between 0.5 and 2 revolutions per second. Rotation at a lower rate leads to the growth of an array of helical columns rather than a dense array of straight columns that are necessary for replication [8]. In contrast, the substrate is held stationary in traditional OAD methods employing thermal evaporation, electron-beam evaporation or sputtering. These traditional methods are able to replicate substrate nonplanarities, although the fidelity of replication begins to diminish as the thin-film coating grows thicker [18]. As the film thickness is increased, any departure from planarity in the substrate creates a disturbance that increases in lateral extent with increasing thickness, the morphology of a growing thin film being governed by the evolution of power-law cones originating from small nucleation clusters or substrate nonplanarities (such as particles and indentations). For high-fidelity replication, the deposited film has to be thin and the practical application of the replica is limited by reduced mechanically stability. Furthermore, substrate features oriented close to the normal to the growth direction cannot be precisely replicated by

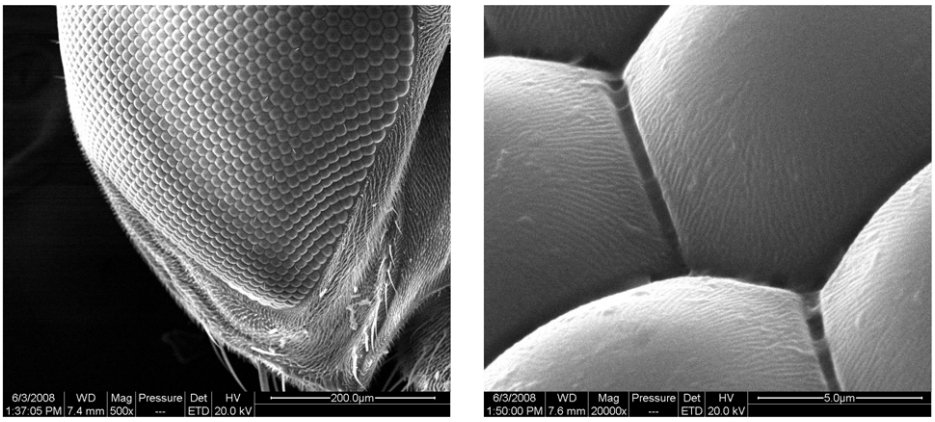


Figure 1. (a) Structure of the eye of a *tephritid* fly (common fruit fly) and (b) detailed scanning-electron microscope image of the eye.

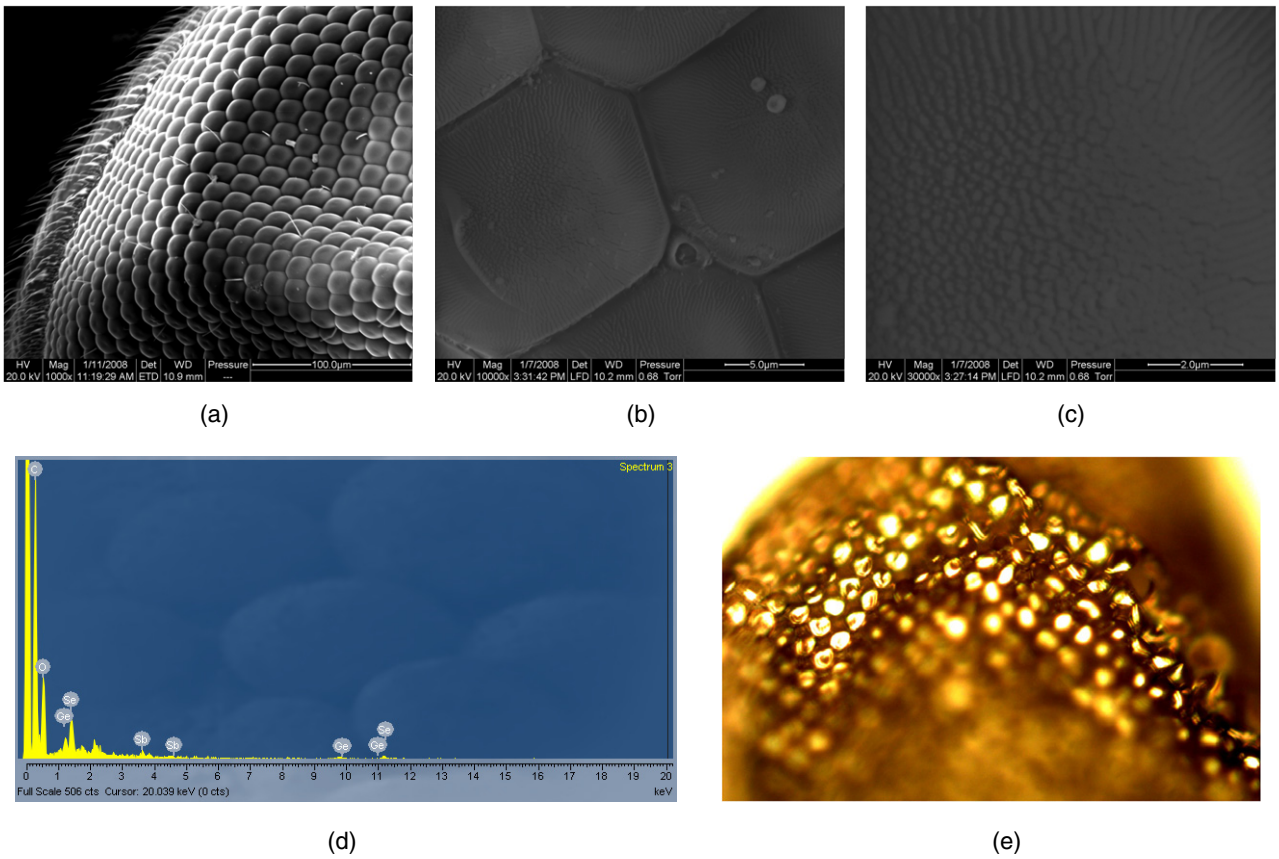


Figure 2. (a) Scanning-electron microscope image of the coated biotemplate. The biotemplate was harvested from the eye of a *tephritid* fly (common fruit fly). (b) Detailed scanning-electron microscope image of the coated structure, showing the areas between the replicated individual *ommatidia*. (c) High-resolution scanning-electron microscope image of the coated structure. Features at the nanoscale are clearly observed. (d) EDS spectrum of the coated structure after GeSbSe deposition by CEFR. (e) Optical microscopy image of a (self-standing) replica. A limited field-of-view in this case must be noted.

the traditional methods, thereby excluding the use of curved substrates. By replicating the spatial features of a curved, micro- and nanostructured biotemplate, we have shown that the CEFR technique overcomes these limitations.

The optical behavior of the replica was determined by measuring its reflectance spectrum, as shown in figure 3. The reflectance spectrum of the original eye of a fly was also measured. From the experimental results, similar spectra in the visible and near-infrared frequency regimes are observed before and after replication, indicating that the structure of the biotemplate was replicated with high fidelity to preserve an optical functionality. The differences observed between

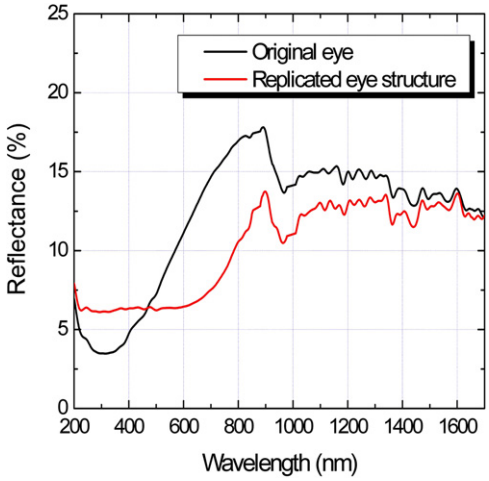


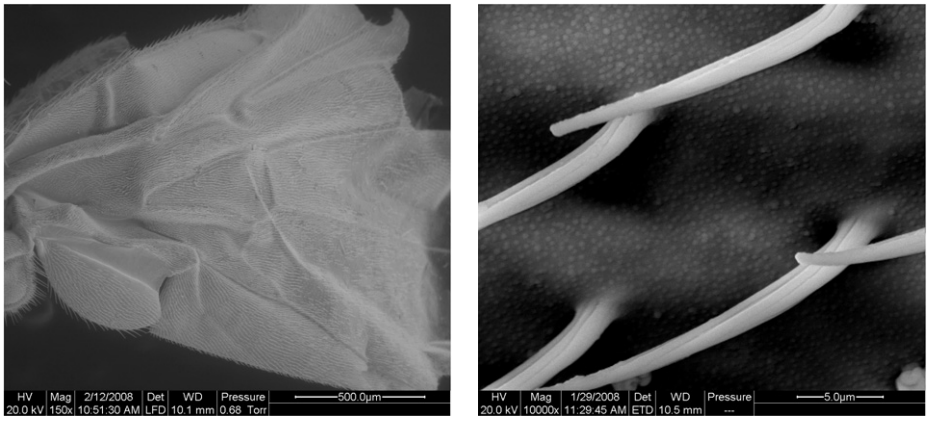
Figure 3. Reflectance spectra of the eye of a fly and the replica.

the optical spectra of the original and replicated templates are attributed to the different frequency dependences of the ocular material and the chalcogenide glass used for the replication. The compound eye and the replica behave, from the optical point of view, as complex diffraction gratings [19]. These gratings, when arranged following a curved corneal area, reduce reflection of incident light compared to a planar and optically smooth surface, thus maximizing light transmission. Accordingly, replicated sub-wavelength structures can be used as antireflection structures leading to increased photon trapping.

Finally, the CERF technique is capable of replicating even more complex structures, which is not possible by the use of conventional thin-film deposition techniques. Figures 4(a) and (b) show, respectively, a general view and a detailed view of the conformally coated wing of a fly. Let us note, in particular, the successful replication of quasi-vertical structures, i.e. the cilia found on the wing surface. Furthermore, the complex structure of the head of a fly is also replicated by the CERF technique, as the images in figures 5(a) and (b) prove.

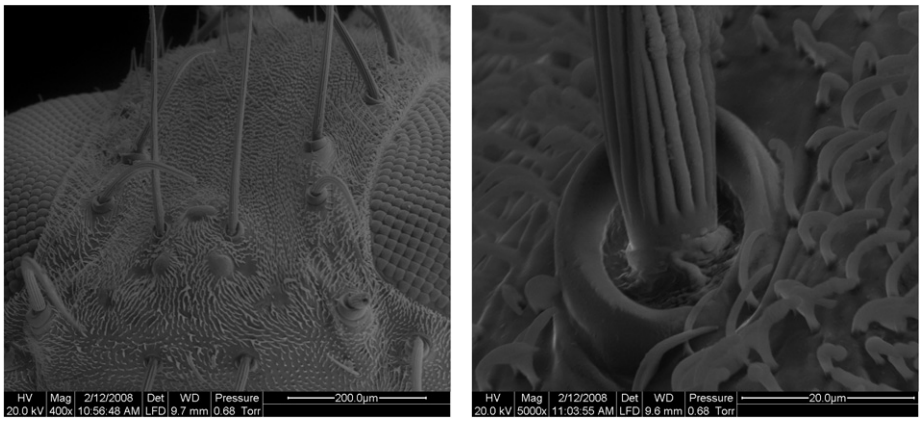
4. Summary and conclusions

In summary, we have devised the CEFR technique to successfully replicate a biotemplate—as exemplified here by



(a) (b)

Figure 4. (a) Scanning-electron microscope image of a conformally coated wing of a fly, and (b) a high-magnification view.



(a) (b)

Figure 5. (a) Scanning-electron microscope image of a conformally coated head of a fly, and (b) a high-magnification view.

the body parts of a fly. The long-range spatial features are replicated on the micron scale, together with the much finer features at the nanoscale. In this respect, for many practical applications replicas of small lateral dimensions are required. We conclude that the CEFR technique to fabricate inorganic replicas of biotemplates is a highly reliable, high-fidelity and low-cost process for fabricating complex nanostructures with biologically inspired functionality.

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