Resonant scattering from silver nanoparticles enhances transparent display performance

Embedding silver nanoparticles in a thin polymer sheet can produce transparent displays based on narrowband resonance scattering phenomena, according to research reported in the January 21 issue of *Nature Communications* (DOI: 10.1038/ncomms4152) by scientists at the Massachusetts Institute of Technology (MIT) and the US Army Edgewood Chemical Biological Center. The frequency-selective properties of these displays, which can be tuned to scatter light of a desired, single wavelength, and their wide viewing angle, make them attractive possible alternatives to currently available transparent displays. Eventually, they might be manufactured inexpensively on a large scale using roll-to-roll polymer processing, which would give them a cost advantage over other display types.

As an example, the head-up display in aircraft that projects flight data on the cockpit window for easy viewing by the pilot works by specular reflection of the images off the glass. This reflection limits the angle of viewing and the images can be seen only from the pilot's seat; they are not visible to someone standing behind the pilot or off to one side. In contrast, the scattering of an image from the new silver-nanoparticle-embedded plastic film can be seen over a wide range of viewing angles. "This makes it useful for viewing by multiple audience members," said Chia Wei Hsu of MIT and Harvard University, the lead author of the article.

The proof-of-concept display developed by Hsu and his colleagues is also more transparent to ambient light than most other types of transparent displays because of its frequency selectivity. By changing the diameter and volume fraction of the silver nanoparticles, it is possible to tune the frequency of light that is scattered. Most head-up displays are not frequency-selective, so basically all of the light is either reflected or transmitted, Hsu said; to reflect more light, it has to be made less transparent. "In our case we can make the display scatter this one particular color but keep the transparency at other colors," he said, "so we won't have to decrease the transparency as much." The research team's display was measured at 60% transparency in the visible range, compared to 20–40% for liquid-crystal displays or organic light-emitting diodes.

The research team chose silver nanoparticles for this initial trial because silver provided the best performance among the materials they had at hand. They mixed hydrolyzed polyvinyl alcohol with an aqueous solution of approximately 64-nm-diameter silver nanoparticles (concentration 0.01 mg/ml), and allowed the solution to dry on a square glass plate over 40 hours. The resulting polymer film had a thickness of 0.46 nm, with nanoparticle density of 7 μg Ag/cm^2. Such a display scatters blue light of 458 nm wavelength.

Hsu and his colleagues see this material as simply a plastic foil that can be placed on glass surfaces, transforming an existing window into a transparent display. For example, an office window with a layer of this foil could be used as a data projection surface while retaining the ability to see through it. Shop windows could be enhanced by projecting product data or branding information on the window's surface to complement the products that are clearly visible behind the screen. Because the scattered light retains the polarization of the incident light, three-dimensional viewing might be achieved by simultaneously projecting two images with different circular polarities and viewing the image through polarized lenses.

Plans for future research include making the resonance band narrower to render the screen more transparent, and to enable the production of three-color displays, instead of the monochromatic display demonstrated in this early work. "In order to enable three-color displays," Hsu said, "we need each of the three resonances [red-green-blue] to be narrow enough so that the three resonances don't overlap each other."

Tim Palucka

Bio Focus

Turkey skin inspires biomimetic sensor

In the United States, turkeys usually only make the press around Thanksgiving, when they play the star role in this annual feast. In Korea and Japan, said Seung-Wuk Lee of the University of California–Berkeley, "they call the turkey the seven-faced bird because it can show seven different colors on its face." For example, when a turkey is excited, the red skin on its face changes to white or blue. Now, the color-changing properties of their skin are inspiring biomimetic sensors that can detect the presence of environmental toxins or explosives.

In the January 21 issue of *Nature Communications* (DOI: 10.1038/ncomms4043), Lee and colleagues from UC–Berkeley, Pusan National University, Sungkyunkwan University, and Korea University have demonstrated that the turkey's structural coloration mechanism can be mimicked using bioengineered phage viruses to create nanostructured surfaces that alter their color in the presence of specific molecules.

The turkey's skin contains nanostructured bundles of collagen protein that interact with the incident light to provide structural coloration. Stimulation triggers swelling of the blood vessels in the turkey's skin, stretching the collagen layer and altering its optical properties and perceived color.

Because of the difficulties associated with synthesizing ordered nanostructures out of unstable collagen bundles, Lee and his team instead used the M13 phage, a bacterial virus that behaves similarly to the turkey's collagen bundles but which can be engineered to display functional peptides. "Tunability is quite challenging in the collagen, but it's very easy to do in the phage," said Lee.

The researchers genetically engineered the M13 phage to recognize target molecules and allowed it to self-replicate. By

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extracting a substrate from a phage solution and controlling the rate of deposition, researchers mediated the phages' self-assembly into a thin-film surface composed of quasi-ordered phage bundles.

In the presence of a chemical vapor, the spacing between the bundles changes; this expansion or contraction alters the coherent scattering of the incident light and, consequently, the surface's structural color. Using an iPhone app that analyzes the color change on an RGB scale, researchers can confirm the presence of a toxin and estimate its concentration.

When composed of wild-type M13 phage, the sensor displayed characteristic responses to humidity changes and volatile organic compounds. However, the sensor also demonstrated selectivity and specificity for molecules with lower vapor pressures, like many explosives and environmental toxins. They engineered a phage surface sensitive to TNT, a common explosive, by modifying the phage to display a TNT-binding peptide motif. As TNT vapor concentration increased, the binding of TNT to the substrate induced structural changes in the phage bundles and a color change of the material.

A key advantage of Lee's design over other colorimetric sensors is the viewing-angle independent coloration of the phage bundles. This color fidelity, combined with the simplicity of fabrication and portability, makes these sensors powerful and practical tools for detecting toxins.

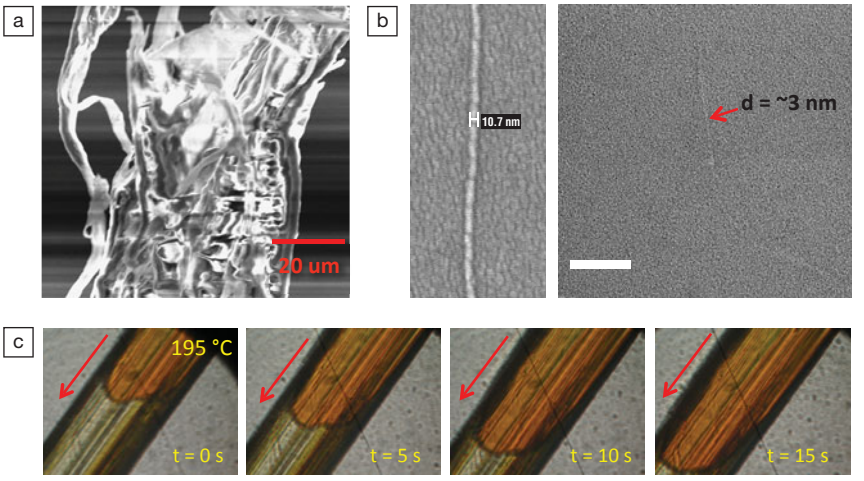
Marya Lieberman studies self-assembly of biomolecules at the University of Notre Dame. "Though the stability, reproducibility, and interferences still need to be characterized, this is a really clever way to translate a chemical interaction on the nanometer scale into a visual output on the centimeter scale. When a sensor can be read visually, it cuts the cost of making the sensor and makes it more practical for field use," Lieberman said.

Laurel Hamers

Light converts monomers into large single-crystal linear polymers

A beaker left in the sunlight has brought the world an unusual class of polymer crystals. A research team based at the University of California at Los Angeles and at Santa Barbara reports in the January 14 issue of *Science* (DOI: 10.1126/science.1245875, p. 272) the quantitative conversion of a class of monomers into large single-crystal linear polymers after exposure to visible light. "This is fascinating because they have a monomer that can undergo a topochemical polymerization to generate enormous [1.5 cm long] single crystals with exceedingly long polymers that are highly oriented," said Paula Hammond of the Massachusetts Institute of Technology. In a topochemical polymerization, monomers are pre-assembled into their approximate end positions, with reaction initiated by heat or light.

"Growth of a polymer crystal is really a pain. What [first author] Letian [Dou] found is a way to trigger the reaction, make everything very simple, and it takes just an hour," said Yang Yang of UCLA, one of the corresponding authors. Fred Wudl (UCSB), the other corresponding author, said, "In general, when anyone does an organic photochemical reaction in the solid state, the product absorbs more than the starting material, and in the same region [of the spectrum, blocking further reaction].... This is probably the first case where a quantitative solid–solid reaction has been observed."



(a) Conventional polymer by mechanical exfoliation versus (b) single-crystal polymer by mechanical exfoliation. Note the entanglement of the conventional polymer. (c) Reversibility: under heating the polymer (yellow) reverts to monomer (orange).

The researchers found that orange-colored crystals of alkylcarboxylate-substituted bis(indene)dione monomers paled and became insoluble when exposed to sunlight or to light from a sodium lamp. X-ray diffraction analysis determined the structure of the resulting polymeric single crystals. R-factors similar to those of the monomer crystals demonstrated a surprising absence of amorphous regions within the polymer. The identity of the alkylcarboxylate side chains is important to the reaction, with 6- and 8-carbon linear alkyl groups maintaining the monomers at the appropriate distance and orientation to permit topochemical polymerization, while smaller or branched alkyl-containing monomers failed to polymerize. The yellow polymer crystals revert at 195°C to orange monomer crystals, which are re-polymerized with light.

"The reversibility is interesting, and is certainly not the case with the diacety-

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