

Smart Nanomaterials

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On-demand switchable materials, such as surfaces that can alter their optical appearance, are ubiquitous in nature. For instance, cuttlefish, a subclass of cephalopods, are experts of camouflage, as they change their body patterns and colors depending on their surrounding environment *via* a visually driven, neurally controlled chromatophore apparatus (Figure 1).¹ Chromatophores contain pigment granules that can be differentially dispersed throughout the cell; when the granules are concentrated in the center of the cell, the cell appears light in color, whereas when the granules are scattered throughout the cell, it appears dark.² Granules are transported rapidly along the cytoskeletal network by motor proteins, and it is this speed by which these granules are transported that enables a quick change in body color. There are many other cases where nature uses time-control very effectively in switching critical properties. Although most synthetic materials still lack such switchability, new synthetic tools and enhanced fundamental understanding have brought such “smart” materials within reach of the materials research community. By definition, smart ma-

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terials are materials that can respond to external stimuli or their environment.^{3,4} Recent examples of smart materials include self-healing polymers that release healing agents upon structural damage,^{5,6} electronic paper displays, whose ink appears or disappears depending on electrical charge,⁷ and meta-materials that serve as an “invisibility cloak” to make objects invisible at a particular wavelength.^{8,9} Analogous to the camouflage behavior of cuttlefish, gels that change color in response to external stimuli such as temperature, pressure, humidity, and salt concentration have been fabricated in the laboratory.¹⁰ By altering the thickness of a thin film composed of alternating layers of two self-assembling polymers, polystyrene and poly(2-vinyl-pyridine), the refractive index of the layer is changed, thereby altering the visible color of the gel. Applications for these gels include colorimetric sensors that detect changes in external conditions, as well as display devices.¹⁰ Given the wide range of uses in nature, smart materials may have a wide range of potential applications in medicine, and many of them, including thermoresponsive hydrogels,¹¹ switchable surfaces,¹² and photoresponsive materials,¹³ have already been explored in this capacity. Another prominent motivation of the quest for synthetic materials with dynamically controlled properties is their potential use as dynamic blueprints in time-resolved self assembly.

Despite this encouraging progress, the implementation of switchable properties will continue to be one of the central obstacles in nanomaterials science in the decades to come. Ultimately, imparting dynamic properties to nanomaterials will result in systems where the materials themselves will be the actual active device. In this issue of *ACS Nano*, Balazs and co-workers describe numerical simulations to predict the switching properties of a smart membrane material.¹⁴ The membrane comprises lipid bilayers in conjunction

ABSTRACT “Smart”

materials—materials that respond to a stimulus or their environment to produce a dynamic and reversible change in critical properties—have enabled progress in many areas, including display technologies, drug delivery, and self-healing materials for coating applications, among others. Many of the current examples of smart materials are biomimetic, since nature employs and depends on dynamic and rapid switching for critical functions such as vision, camouflage, and ion channel regulation. Despite progress in designing smart materials and surfaces, much work is still needed in this area to increase their implementation in useful applications. In this Perspective, the challenges and outlook in this field are highlighted, including the work of Balazs and co-workers found in this issue of *ACS Nano*.

See the accompanying Article by Alexeev *et al.* on p 1117.

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Figure 1. Camouflage of a cuttlefish that mimics its environment, in this case a checkerboard.¹ Republished with permission from ref 1. Copyright 2006 Elsevier.

with amphiphilic Janus particles. In contrast to conventional lipid bilayers, lipid membranes embedded with Janus particles bearing hydrophilic and hydrophobic moieties form stable pores upon perforation by mechanical force. When opening the pore, Janus particles expose their hydrophilic portion to the solvent. As the mechanical force is reduced, particles that lined the pores migrate toward each other until they form stable clusters. Thus, the pore never completely closes and remains as a stable hole due to the self-assembled cluster of particles (Figure 2). If re-exposed to the initial stimulus, the pore can reopen, which is in clear contrast to lipid bilayers without anisotropic particles. As a consequence, the composite membrane can open and close on demand. In this way, a smart property has been imparted to the membrane, resulting in stimuli-responsive pores that can be

opened and closed controllably and reversibly. It can be expected that membranes such as the example that Balazs and co-workers present can selectively control transport of materials and may find potential use in self-healing materials, nanofluidics, and drug delivery.

Fundamentally, the system studied by Balazs and co-workers is intriguing in that it combines an oriented interface, the lipid bilayer, with anisotropic particles. Thus far, activities toward smart materials have exploited two lines of design (Figure 3). The first approach is the design of surface coatings or bulk materials that undergo reversible molecular transitions depending on the presence or absence of a stimulus. Stimuli include changes in pH, salt content, temperature, the presence of a specific analyte, electrical or magnetic fields, or light. A second approach takes advantage of anisotropic particles that can change surface

properties if oriented at an interface in a controlled manner.

Conformation-Based Switching. A number of smart surfaces have been developed that can switch surface properties upon exposure to internal

or external stimuli. Well-known examples include stimuli-responsive polymers, such as poly(*N*-isopropyl acrylamide) (pNIPAAm). This thermoresponsive polymer has been widely explored for a variety of biomedical applications including drug delivery (recently reviewed in refs 15–19), modulation of cell adhesion and protein adsorption,^{20–22} and cell sheet engineering.²³ Another class of biologically inspired thermoresponsive molecules is based on elastin-like polypeptides (ELPs). These polypeptides contain the valine-proline-glycine-*X*-glycine motif, where *X* may be any amino acid other than proline.²⁴ The molecules are water-soluble at lower temperatures but reversibly aggregate at elevated temperatures. The switching can be induced by changes in temperature, pH, or ionic strength.^{25,26} Elastin-like polypeptides have been micropatterned to capture and to release other proteins fused to ELPs *via* hydrophobic interactions upon transition.²⁷

In addition to temperature, light can also serve as a stimulus, providing an alternative to actuate the smart properties in applications where temperature changes may not be a viable option. Several chemically triggered systems that change wettability upon light irradiation include azobenzene,²⁸ pyrimidine,²⁹ *O*-carboxymethylated calix[4]resorcinarene,³⁰ or spiro-pyran³¹ groups. More recently, shape-memory polymers that respond to UV light have been reported.^{13,32,33} Such polymers are composed of an elastic polymer network and a molecular switch, which determines their permanent shape and forms reversible crosslinks upon photostimulus, respectively.³⁴ This polymer can change from its flat ribbonlike structure to a tight coil, then back to a ribbon, in response to light.¹³

Alternatively, electrochemical transformations of self-assembled monolayers (SAMs) have been explored to produce smart substrates.

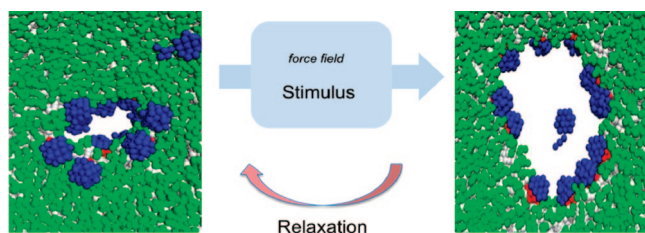


Figure 2. Smart membrane system consisting of anisotropic particles embedded in a lipid bilayer. Adapted from ref 14. Copyright 2008 American Chemical Society.

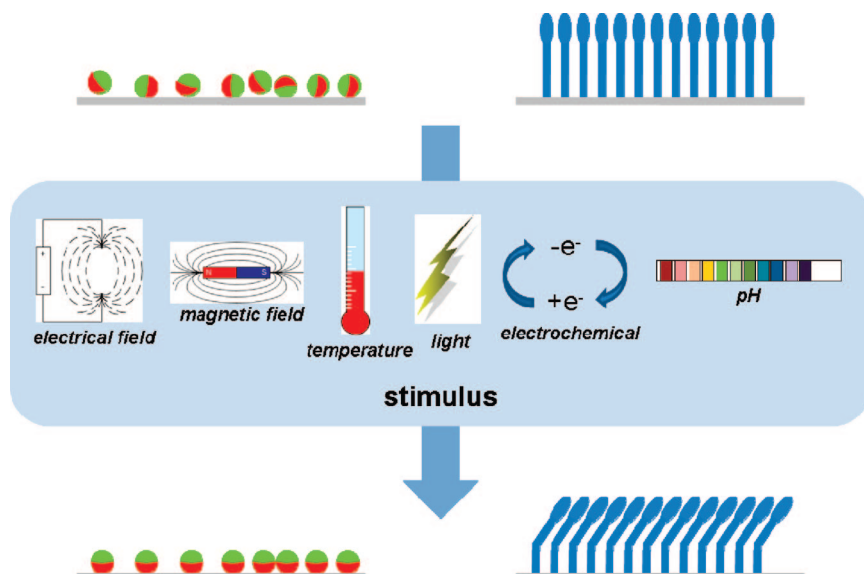


Figure 3. Two potential approaches toward the design of smart materials. The orientation of anisotropic particles (left) as well as the conformation of molecular switches (right) are altered relative to a surface by application of a stimulus. The switching results in different surface properties.

For example, alteration in surface wettability has been shown upon application of electrical potentials in combination with SAMs of alkanethiols on gold.³⁵ In this system, a decrease in contact angle of $>80^\circ$ to 0° was observed. In another approach, conformational switching of surface-confined molecules was used to control interfacial properties dynamically.³⁶ Similarly, control of molecule concentration spatially and temporally by taking advantage of surfactant desorption has been reported.³⁷ By using electrodes, surfactants bearing redox-active groups were alternated between surface-active or -inactive forms, changing the surface pressure, enabling control of the position and motion of liquids. In yet another approach, electrical potential was used to trigger conformational transitions of alkanethiols on gold, while maintaining constant environmental parameters (solvent, electrolyte content, pH, temperature, and pressure).³⁶ A mercaptohexadecanoic acid derivative containing a globular end group was used to form a SAM whose end groups were tightly packed, while maintaining uniform spacing at the gold/thiol interface and in between the hydrophobic chains.³⁶ Follow-

ing cleavage of the bulky end group, a mercaptohexadecanoic acid SAM of low density resulted, allowing the hydrophobic chains to alter their conformation reversibly in response to changes in the electrical potential. This change in conformational transition led to changes in surface wettability, thereby allowing dynamic control of interfacial properties. Other electrochemically driven switchable surface designs to control surface wettability include gold electrodes coated with monolayers of bipyridinium-containing thiols,³⁸ rotaxanes,³⁹ and pseudorotaxanes, which result in surfaces that capture and release aromatic guest molecules.⁴⁰

Anisotropy-Based Switching. While all of these examples exploit structural transitions in molecular systems with appropriate energy balances between two or more states, surfaces that switch based on orientational changes of anisotropic particles at an interface can also be envisioned. Such an approach requires the availability of particles with distinct differences in their appearance depending on from which side they are observed (Figure 4). Synthesis of anisotropic particles goes well beyond efforts established for

centro-symmetric particles. Successful methods include the use of a spinning disk,^{52,53} self-assembly,^{54,55} fusion of pre-existing particles,⁵⁶ surface modification with partial masking,^{57–60} selective deposition,^{61,62} surface modification through partial contact with reactive media,^{63–65} microcontact printing,^{47,66} and template-assisted self-assembly.^{67,68} Other examples include heterodimer nanoparticles,⁶⁹ solidified paraffin droplets,⁷⁰ and magnetic microbeads.⁷¹ For

certain materials, dumbbell-, snowman-, or acorn-like nanoparticles have been developed. Known methods include controlled crystallization from precursor core-shell particles^{72,73} and selected surface nucleation.^{74–76} In related work, Rainer *et al.* employed polystyrene-*b*-polybutadiene-*b*-poly(methyl methacrylate) and similar polystyrene-*b*-polybutadiene-*b*-poly(methacrylic acid) triblock copolymers for the synthesis of Janus micelles.^{77,78} These triblock copolymers have well-defined bulk morphologies due to their unique microphase separations. After following the selective cross-linking reaction of core polybutadiene blocks, dissolution of the bulk materials yielded anisotropic micelles.

Among the most promising processes currently under evaluation for fabrication of anisotropic particles are methods based on the relatively simple manipulation of liquids followed by rapid solidification. In this way, multicompartiment particles with nonequilibrium materials distributions can be fabricated in large quantities. Solidification must occur sufficiently quickly to prevent mixing between temporarily formed compartments. By using flow-focusing technology,^{79–81}

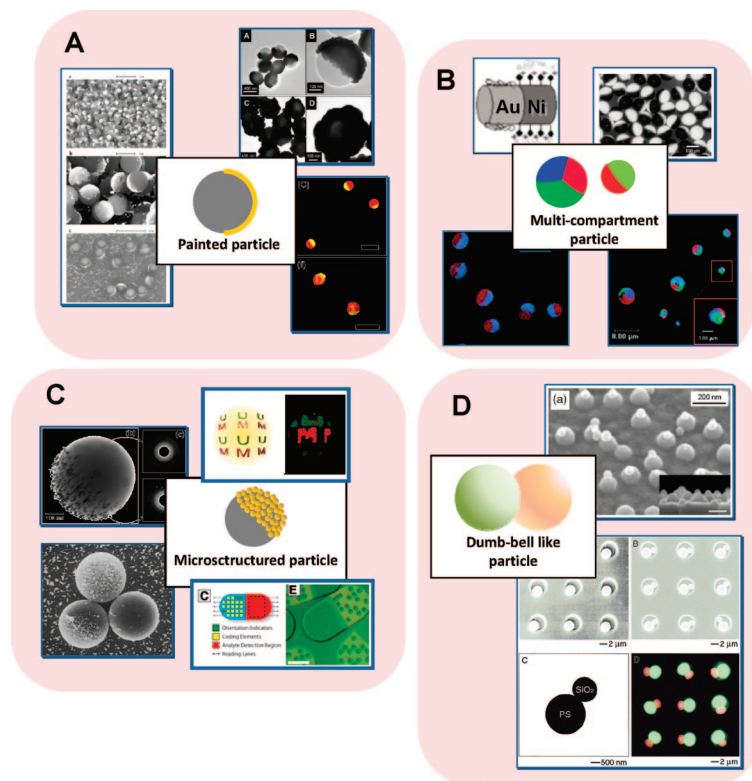


Figure 4. Representative examples of anisotropic particles with potential for anisotropy-based switching. (A) Painted particles include particles that were selectively modified by gel-trapping,⁴¹ metal deposition,⁴² or layer-by-layer deposition.⁴³ (B) Multicompartment particles include bimetallic nanorods⁴⁴ and larger microbeads,⁴⁵ as well as triphasic⁴⁶ and biphasic nanocolloids. (C) Dumbbell-like particles are made by fusion of different types of particles.^{47,48} (D) Microstructured particles include particles with controlled topology⁴⁹ and lithographically modified particles,⁵⁰ as well as encoded particles⁵¹ and those prepared by metal evaporation and chemisorption onto latex particles.⁶² Caption assignments are made clockwise starting in the upper left quadrant. Image credits are listed clockwise within each respective quadrant. (A) Republished with permission from ref 41, 2004 Wiley-VCH Verlag GmbH & Co.; from ref 42, 2006 Springer; from ref 43, 2005 American Chemical Society. (B) Republished with permission from ref 44, 2003 Macmillan Publishers Ltd.; from ref 45, 2006 Wiley-VCH Verlag GmbH & Co.; from ref 46, 2006 American Chemical Society; from Bhaskar and Lahann, unpublished data. Republished with permission from ref 47, 2004 Wiley-VCH Verlag GmbH & Co.; from ref 48, 2001 American Chemical Society. (D) Republished with permission from ref 49, 2008 American Chemical Society; from ref 50, 2007 The National Academy of Sciences of the United States of America; from ref 51, 2007 American Association for the Advancement of Science; from ref 62, 1997 American Chemical Society. The four center images are original.

microdroplets containing chromophore molecules and biomolecules in separate phases have been generated and cured by appropriate cross-linking mechanisms.^{82–84} Larger biphasic and multiphase particles with diameters of 50–150 μm and narrow size distributions were prepared using microfluidics.

Other examples include the fabrication of microparticles using hydrodynamic jets,^{85–87} or electrohydrodynamic cojetting.⁸⁸ A prominent strategy toward anisotropic micro- and nanoparticles uses

electrohydrodynamic cojetting.^{46,88} In this method, the interface between the two jetting solutions is sustained during jet fragmentation and size reduction. In principle, such novel particle geometries enable independent control of key parameters, such as chemical composition, surface functionalization, biological loading, shape, and size for each compartment, thereby effectively mimicking the architecture of biological cells. This approach toward designer nanoparticles leads to unique capabilities that enable

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the design of particles with multiple and distinct surface patterns or nanocompartments. Because of its intrinsic simplicity and generality, the electrohydrodynamic cojetting process can be applied to a wide range of specialty and nonspecialty materials including many FDA-approved materials.^{89,90} The fact that each compartment can be designed independently from the other compartments affords anisotropic particles with multiple, orthogonal materials functions. In particular, electrohydrodynamic cojetting can be employed successfully in cases where the functions of incompatible materials must be engineered in close proximity to one another.

SUMMARY

Major efforts have been undertaken to create increasingly sophisticated materials that start to mimic biological materials with respect to precision, architecture, and functionality. Still, most of today's materials are intrinsically static. In other words, what sets today's synthetic materials apart from biological materials is the ability to undergo defined changes in key properties over time. Combinations of theoretical and experimental methods will significantly widen the design parameters available for smart materials. In this regard, the study by Balazs and co-workers is remarkable. Their theoretical results suggest that through simple introduction of

anisotropic particles into lipid bilayers, responsive pores could be created, which can open and close on demand. Although their study focuses on reversible switching due to mechanical forces, alternate triggers such as temperature or pH may also be explored for switching. Beyond the smart membrane studied by Balazs and co-workers, materials containing anisotropic particles can be expected to find applications in fundamental studies of cell architecture as well as in biomedical applications, such as drug delivery or molecular imaging. Despite the impressive advances recently made with switchable materials, even our most basic understanding of surface processes involving molecular switches as well as multicompartment particles is still rudimentary, and much work lies ahead in developing synthetic analogues of switchable systems, such as those used for camouflage by the cuttlefish.

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