Making Things by Self-Assembly

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Abstract

Self-assembly—the spontaneous generation of order in systems of components—is ubiquitous in chemistry; in biology, it generates much of the functionality of the living cell. Self-assembly is relatively unused in microfabrication, although it offers opportunities to simplify processes, lower costs, develop new processes, use components too small to be manipulated robotically, integrate components made using incompatible technologies, and generate structures in three dimensions and on curved surfaces. The major limitations to the self-assembly of micrometer- to millimeter-sized components (mesoscale self-assembly) do not seem to be intrinsic, but rather operational: self-assembly can, in fact, be reliable and insensitive to small process variations, but fabricating the small, complex, functional components that future applications may require will necessitate the development of new methodologies. Proof-of-concept experiments in mesoscale self-assembly demonstrate that this technique poses fascinating scientific and technical challenges and offers the potential to provide access to hard-to-fabricate structures.

Keywords: *biomimetic materials, electronic materials, mesoscale, microfabrication, optical materials, self-assembly, surface chemistry, templating.*

Introduction

"Making things" is one of the central activities of human life. Between eating, sleeping, procreating, and watching TV, out of necessity or from sheer esthetic pleasure, we spend much of our time fabricating structures of a wide variety of complexities, purposes, sizes, and costs. The set of tools that we have developed to this end is extensive. It includes methods to manipulate matter at scales ranging from tenths of nanometers to thousands of kilometers. Among these methods, four deserve special mention: (1) chemical synthesis, which uses atoms to make molecules; (2) photolithography, which uses patterns of light to make patterned materials; (3) mechanical manufacturing, which uses techniques such as casting, stamping, and machining to make parts, and uses mechanical devices to assemble the parts into functional machines; and (4) construction, which uses materials to build large or extensive structures such as highways. We may in the future add to this list "growth," which will summarize the generation of living things as a form of engineering. A common characteristic of the four current methods is that they all require human intervention: without the human hand to hold the vial (or to make and program the robot that replaces the hand), the product will not appear.

Things, however, can also be made in a different way and without a guiding hand: that is, by self-assembly (Figure 1). "Self-assembly" was originally defined in molecular systems as a process in which molecules or parts of molecules spontaneously form ordered aggregates, usually by non-covalent interactions;[1] examples range from formation of crystals and micelles to formation of complex organic and organometallic molecules by design.[2–4]

Countless examples of self-assembled molecules, materials, and systems can also be found in nature. Protein molecules synthesized as linear chains spontaneously fold into functional 3D structures of complex topology; aggregates of proteins and nucleic acids become the catalysts that regulate synthesis, sensing, and signal transduction in the living cell; cells divide, develop, and organize to become whole organisms. Self-assembly is now being intensely studied in chemistry, biology, and materials engineering, in systems ranging in size from molecular to macroscopic.

We would like to suggest that self-assembly—a strategy highly developed with molecules—can also be applied to components ranging in size from nanometers to millimeters (mesoscale self-assembly, or MESA), and that this form of self-assembly offers a new strategy for "making things" that cannot be made otherwise. We believe that, as a fabrication strategy, it is particularly useful in making structures that are too large to be prepared by chemical synthesis, but too small to be made (or assembled from individual components) by the methods—manual, mechanical, or robotic—commonly used for such purposes. We call this scale the *meso*scale: in between chemical (bottom-up) synthesis and more familiar (top-down) forms of fabrication.

This article will discuss the characteristics of mesoscale self-assembly that make it an attractive area of research and that may make it practically useful in microfabrication, review some recent developments in the area of mesoscale self-assembling systems of components with micrometer to millimeter sizes, and outline some of the most important unsolved problems that this type of self-assembly now faces as a branch of science and as a potential technology.

Making Things Out of Molecules Using Self-Assembly

The interest in molecular self-assembly originated in chemistry and was stimulated both by the central importance of self-assembly to life (e.g., protein folding, formation of lipid bilayers) and by its ubiquity in chemistry (e.g., crystallization, formation of vesicles, adsorption on surfaces, and supramolecular chemistry).[5] Reversible noncovalent interactions—that is, attractive and repulsive forces having values of energy close to thermal energy—between large numbers of components (molecules or parts of molecules), often embedded in pairs of molecules with complementary shapes, underlie these processes. Agitation in these systems—and thereby, encounters between the components—is provided by their thermal motion, and these agitations often allow the self-assembly to be reversible (an important matter in achieving ordered structures). Reversibility allows components to readjust their relative positions to form aggregates without defects. Templating—the imposition of geometrical constraints, or the introduction of loose connections between the components, in ways that limit the range of structures that self-assembly can form—also plays an important role in many molecular processes. Molecular self-assembly can be *equilibrium*

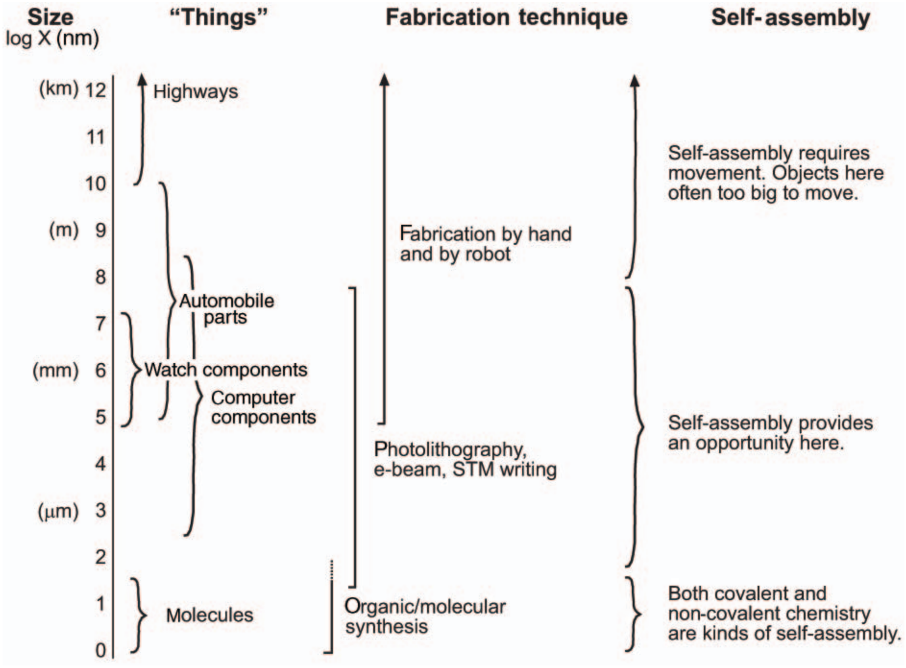

Figure 1. Chart illustrating the general scheme of "making things" at size scales ranging from nanometers to kilometers, and the possible niches for application of mesoscale self-assembly.

(i.e., static and involving structures that rest in energy minima) or *dynamic* (i.e., involving structures whose existence depends on the dissipation of energy).

Molecular self-assembly is also of practical interest for the disciplines concerned with making molecules and molecular materials:[6,7] examples include non-covalent synthesis,[8,9] crystallization,[10] micelle formation,[11] surfaction, and phase-separation in block copolymers.[12,13] Self-assembled monolayers[14] (SAMs) have proven to be a particularly useful system, as they make it possible to engineer extended macroscopic surfaces with nano-scale control of the properties.[15]

Self-assembly of molecules is ubiquitous, vitally important, and entrancingly interesting, but limited in the kinds of structures it can make and the range of functions that it can generate. Molecules are quite inflexible in several ways: one cannot, for example, tailor the interaction potential between the components/molecules, because the interactions—both covalent and non-covalent—between molecules or atoms are based on their intrinsic properties (ultimately, their electronic structure). The non-covalent interactions that are centrally important in self-assembly are a small set (van der Waals interactions, electrostatic and hydrophobic interactions, and hydrogen-bonding interactions). These interactions generally do not support electrical or magnetic function.

Studies of molecular self-assembly have been stimulated by studying living systems, but so far they have abstracted and tried to mimic only a tiny subset of the phenomena that occur there. Research has focused almost exclusively on equilibrium systems; many (perhaps most) of the most interesting processes in the living organisms take place far from equilibrium.[16] Only a limited range of functions can be accessed using molecules as functional components: a useful transistor has not yet been demonstrated in a molecular system, and ways to position and connect molecules into a functional electronic device have yet to be developed.[17]

New Scales for Self-Assembly: Systems Based on Objects with Micrometer to Millimeter Sizes (Mesoscale Self-Assembly)

Most of the concepts and general principles of self-assembly were developed or elucidated in molecular systems. Components of any size, however, can self-assemble under appropriate conditions.[18] Self-assembly of micrometer- to millimeter-sized components offers flexibility in design and access to types of functionality unparalleled by molecular systems. Three characteristics make self-assembly in this range of sizes an especially attractive new area of research: (1) In systems of components bigger than molecules, one can employ a wider range of interactions (e.g., capillary, electrostatic, magnetic, optical, fluidic shear, gravitational) between the components than in molecular systems. One can also engineer separately the attractive and repulsive interactions between the components. (2) Self-assembly of micrometer- to millimeter-sized components offers a flexible route to the fabrication of 3D and large-area structures; such structures are often not easily generated using photolithography or e-beam writing. (3) In these systems, it may be possible to generate new types of functionality or combinations of functionalities (e.g., electrical and fluid transport).

Our approach, used also by others, to studying self-assembly in non-molecular systems has been based on learning from molecules. We abstract the basic principles that govern self-assembly in molecular systems and apply them in systems comprising millimeter-scale components. Our ultimate goal is to be able to use this knowledge to make micro- and nanoscale structures with functionalities that chemists often do not deal with (magnetic or electric/electronic). To achieve this goal, we need to understand both the *similarities* and the *differences* between the key characteristics of mesoscale self-assembly and the strategies used in making things by self-assembly in the molecular and microscopic size regimes.

1. Components: size, number, fabrication, structure, and functionality. In MESA, the final structure is made from individual components. Whatever the desired function is, that function (or the *potential* for it) must exist in the components. The fabrication of large numbers (10^3–10^6 in research demonstrations) of the appropriate components is a daunting task. How, for example, would one fabricate micrometer-scale cuboctahedra in silicon with solder dots on some faces and microcircuits on others? We simply do not know how to make such structures, although all of our experience indicates that they would self-assemble well if we *could* make them.

2. Motion/agitation. The components in self-assembling systems must be able to move and to interact as a result of encounters between them. The number of encounters between molecules, and the on- and off-rates of formation and dissociation of molecular aggregates, are much higher than those in mesoscale systems. In solution, thermal motion suffices to bring molecules in contact, while in mesoscale systems the motion of components has to be provided by an external source (e.g., shaking or stirring).

3. Interactions. In both molecular and mesoscale self-assembling systems, the components interact by a balance of attractive and repulsive forces; the formation of ordered aggregates in both size regimes requires that the interactions between the components be reversible or that the components be able to adjust their respective positions.[19] Shape complementarity of the interacting surfaces of the components is often a factor in the molecular interactions, and is widely used in human-directed fabrication; due to fabrication difficulties, it is only beginning to gain use in mesoscale systems.

4. Templating. In all three size regimes, templating is often used to limit the number of structures that can be created and to prevent the formation of defects, especially in the case of systems comprising numerous components. Templating at all scales can be accomplished either by connecting the components in a way that limits the modes in which they self-assemble or by providing structural "guides" to control the self-assembly. The formation of aggregates of mesoscale and macroscopic components can be templated very simply by using containers of the right size and shape; this type of templating is normally not possible in molecular systems, since containers of molecular size are seldom available.[20]

Examples of Mesoscale Self-Assembly

The following examples illustrate some areas of interest in the field of mesoscale self-assembly:

1. Functional self-assembled systems. We and others have begun to investigate the possibility of self-assembling micrometer- to millimeter-sized components into simple electronic devices and structures with electrical connectivity (see References 18 and 21, and references therein). Our approach is based on using capillary interactions and minimizing the interfacial free energy (and thus the surface area) of liquid solder to drive the self-assembly. The solder, when solid, provides both mechanical stability and electrical connectivity in the system. Surface-tension-based self-assembly was also used to fabricate optically active materials,[22] to form the 3D structure of mechanical and microelectromechanical (MEMS) systems,[21] to position optical elements in micro-optoelectromechanical (MOEMS) devices,[23] and (in combination with shape complementarity) to integrate electronic circuits onto rigid and flexible substrates[24] (Figures 2a–2c).

2. Self-assembly using spontaneous folding. We and others have developed a new strategy for the formation of 3D objects; this strategy combines the existing highly developed and very efficient methods for planar microfabrication (photolithography and soft lithography) with self-assembly (see References 21 and 31, and references therein). In a recent example, we designed a system in which flat, elastomeric sheets patterned with magnetic dipoles spontaneously folded into free-standing, 3D objects that are the topological equivalents of spherical shells.[28] The path of the self-assembly was determined by a competition between mechanical and magnetic interactions. Figure 2d shows an elastomeric globe fabricated by self-assembly starting from a flat, 2D projection of the Earth. We demonstrated the potential of this strategy for the fabrication of 3D electronic devices by generating a simple electrical circuit surrounding a spherical cavity (Figure 2e).

3. Hierarchical self-assembly. The principle of hierarchical organization of components into increasingly complex structures is well known from molecular self-assembly in biological systems.[35] We have used hierarchical self-assembly of spherical beads with dimensions of 100–1000 mm to generate extended 3D lattices with high symmetry[29] (Figure 2f). In this work, we first assembled rods of different geometry by packing the beads in confined columnar wells. Self-assembly of these rods led to the formation of regular 3D arrays with structures that had not been accessible nor easily fabricated by previously developed methods.

4. Templated self-assembly. The formation of the functional, 3D structures of biological macromolecules is usually facilitated by constraining the process of self-assembly. We and others have applied the same strategy (a form of templating) in meso-scale self-assembling systems to control the 3D structures of the resulting aggregates (see Reference 36 and references therein). In processes analogous to constrained (bio)molecular self-assembly, we used several mechanisms to template the outcome of self-assembly: geometrical restriction of the space in which self-assembly takes place[37,38] (Figure 2g); restriction of the order of the components by connecting them in a chain of predefined sequence[31,39] (Figure 2h); and self-assembly in the presence of a second ordering moiety, for example, liquid drops to guide the formation of spherical aggregates of colloids[32] or hexagonal metal plates[33] (Figures 2i and 2j).

5. Reconfigurable self-assembling systems. Molecular systems that change shape when environmental conditions change are common: the changes in shape of polymers with ionizable groups[40] and of proteins[41] provide two examples; others include melting of molecular crystals[42] and phase-separation in block copolymers,[43] both with temperature. We have designed primitive adaptive systems in which the individual components formed several stable, structurally different aggregates.[34,38,44] In one example, a set of millimeter-scale objects self-assembled at the interface between an aqueous solution and perfluorodecalin into two different, regular aggregates, with the choice between them determined by the density of the aqueous phase (Figure 2k).

Mesoscale Self-Assembly May Offer a New Approach to Microtechnology

The self-assembly of non-molecular components is beginning to show its potential in academic demonstrations as a strategy for forming interesting and useful structures. Several characteristics of these systems suggest that self-assembly may become technologically important for the various microtechnologies—for example, microelectronics, micro-optics, MEMS, and microanalytical systems—and for materials science:

1. The greatest strength of self-assembly is that it allows the organization of small and numerous components into ordered structures (both in two and three dimensions) in a parallel process. The techniques currently used to generate 3D structures (e.g., monolithic microfabrication, surface patterning, laser micromachining, multiphoton polymerization, and LIGA*)[45] are precise and versatile, but have high capital costs and are limited in the range of materials that can be used and the structures that can be generated. Most microfabrication procedures are based on photolithography, an inherently planar technology.

An alternative strategy in microfabrication is to build the desired object using the assembly of prefabricated parts. In microassembly using high-accuracy robots or micro-grippers ("pick-and-place"), the components can be placed with submicrometer accuracy, but it is usually done in a serial process. This process is slow, expensive, and not suitable for positioning parts with dimensions of <100 μm.[46]

The methods developed for flip-chip wafer-to-wafer transfer allow for simultaneous, parallel transfer of numerous prefabricated components from a donor to a target wafer—a technique known as "deterministic microassembly." Parts with di-

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*LIGA is the German acronym for Lithographie, Galvanoformung, und Abformung (lithography, electroplating, and molding), a strategy for the microfabrication of high-aspect-ratio structures out of metals, metal alloys, plastics, or ceramics.

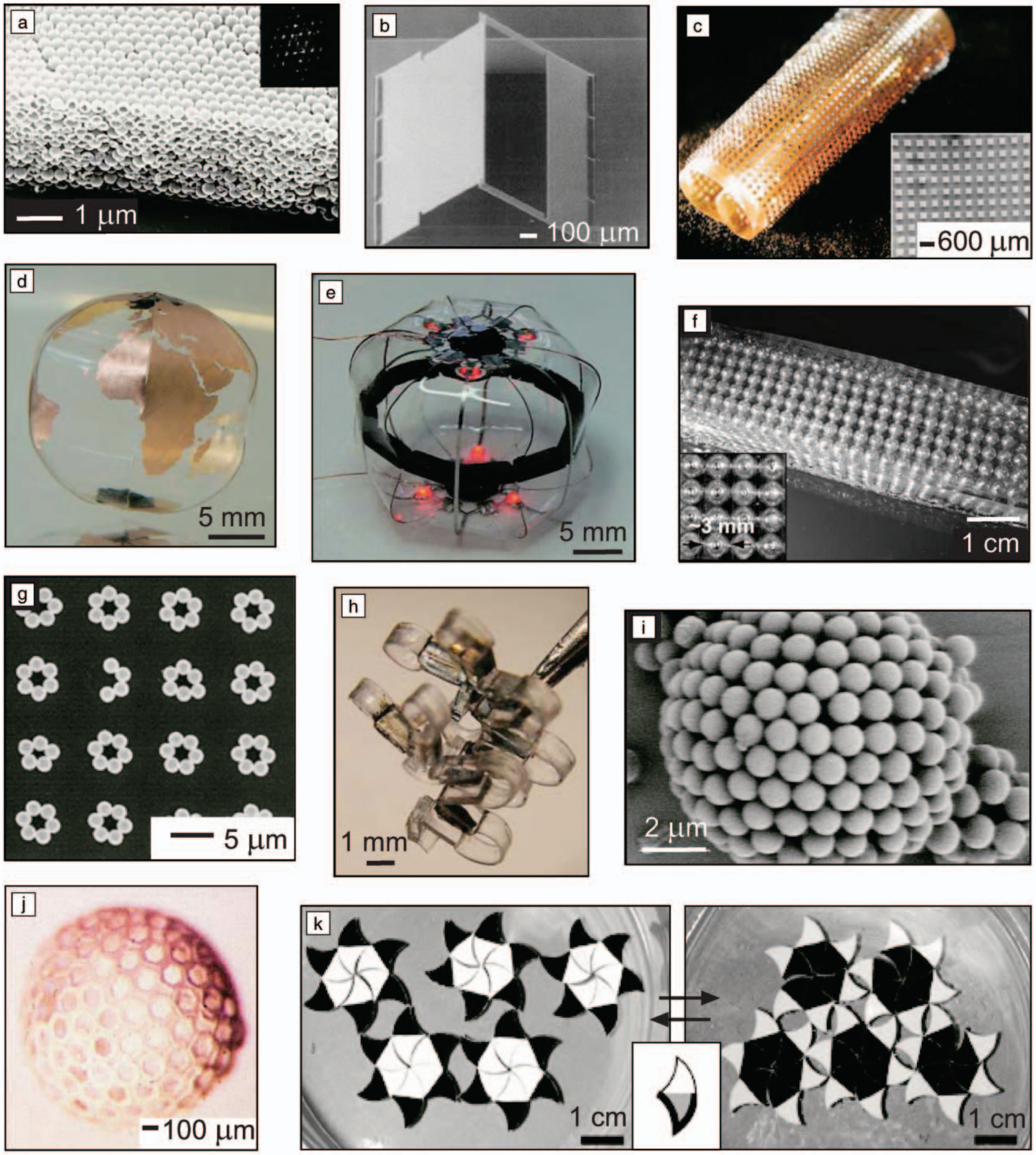

Figure 2. Examples of self-assembled mesoscale structures. (a) A hollow TiO_2 colloidal crystal. The inset shows Fourier transform of 40 µm × 40 µm region in the (111) plane of the crystal. (Reprinted in part with permission from Reference 25.) (b) An asymmetric, 3D silicon micromirror formed from a planar precursor by surface tension-powered self-folding. (Reprinted in part with permission from Reference 26.) (c) A large-area array of silicon segments self-assembled on a flexible, nonplanar support. The inset shows a detail of the structure. (Reprinted with permission from Reference 27.) (d) An elastomeric globe self-assembled from a flat, 2D projection of the Earth.[28] (Image: M. Boncheva.) (e) A simple 3D electrical circuit surrounding a spherical cavity. (Reprinted in part with permission from Reference 28.) (f) A self-assembled simple-cubic lattice of brass beads. The inset shows a detail of the structure. (Reprinted in part with permission from Reference 29.) (g) An array of ring-shaped aggregates of polystyrene beads. (Reprinted in part with permission from Reference 30.) (h) A 3D helical structure self-assembled from a crimped elastomeric tape. (Reprinted in part with permission from Reference 31.) (i) A dried hollow capsule (colloidosome) composed of polystyrene spheres. (Reprinted with permission from Reference 32.) (j) A porous sphere composed of hexagonal rings self-assembled on a drop of chlorobenzene in an aqueous silver-plating solution. (Reprinted in part with permission from Reference 33.) (k) Two different ratchet wheel structures with opposite chirality self-assembled from the same precursor (inset). (Reprinted in part with permission from Reference 34.)

mensions of 10–4000 μm can be transferred in a single step, with a yield of >99% and precision of ±0.1 μm.[47] A drawback of this approach, however, is that the tethers supporting the microfabricated components and the solder bumps that attach them to the target wafer occupy too much surface area; this approach, therefore, is not appropriate for the manipulation of large numbers of very small components or for situations in which small components must be positioned sparsely onto a large-area structure. Further, this method, as commonly practiced, is limited to planar surfaces.

Self-assembly is probably the only practical way to manipulate and order nano- and micrometer-sized components into 3D structures: in this size regime, the components are too big to be manipulated using molecular techniques, but are too small to be manipulated conveniently using external manipulation. Self-assembly can form repetitive 2D and 3D structures with high symmetry (analogues of molecular crystals) *and* asymmetric structures (analogues of macromolecules). The process of self-assembly itself is compatible with a wide variety of materials: semiconductors, glasses, plastics, and metals. There are no intrinsic limitations regarding the number of components that can be assembled simultaneously in a parallel process; commercially, fluidic self-assembly has been developed by Alien Technology Corp. to position tens of thousands of chips with dimensions of between ten and hundreds of micrometers on a common substrate during the fabrication of RFID tags.[24] Self-assembly also, in principle, makes it possible to position and connect components in cavities inaccessible to robotic arms as well as to tile curved surfaces.

2. Self-assembly provides access to aggregates with electric/electronic or optical functionality. The components in a self-assembling system can be decorated with electronic devices; in initial (and still crude) demonstrations, we and others have designed systems in which self-assembly leads to the formation of electrical connections between electronic components (see Figure 2e).[18] Importantly, the resulting aggregates have a truly 3D structure; at present, the microfabrication of 3D architecture in electronic devices is limited mostly to stacking (or sometimes folding) of planar sheets.[48]

Self-assembled aggregates can also have valuable optical properties. The size range—nanometers to millimeters—of components that can be crystallized into 3D structures is compatible with the requirements for optical activity. The generation of photonic-bandgap materials by self-assembly is being actively pursued by a number of groups.[49–51]

3. Components fabricated using incompatible processes and materials can be combined in the same self-assembled aggregate. The availability of inexpensive devices that combine optical and electronic functionality is potentially important in data processing and telecommunications. The fabrication of such hybrid devices must usually combine complementary metal oxide semiconductor (CMOS) technologies (for microelectronics) and III–V technologies (for optics), a task which is often made difficult (and sometimes impossible) by process incompatibilities. Self-assembly may make it possible to circumvent some of the problems of incompatibility in the fabrication of hybrid devices, since the processing of the different types of components can be done separately and the components—appropriately functionalized—can be integrated using self-assembly, rather than combining the different technologies in a single process.

4. Self-assembly allows one to achieve very high accuracy of registration in positioning small components. In many currently available micropositioning systems with large working ranges, mechanical friction often limits resolution to a few micrometers. Positioning systems with nanometer resolution are available, but achieving a large working range at low cost is difficult. The pick-and-place robotic devices employed by the microelectronics industry have high positioning accuracy, but can handle only standardized mechanical parts and allow implementation of only standardized operations. The precision achieved in wafer-to-wafer transfer is about 0.1 μm.

The best positioning accuracy achieved in self-assembly compares favorably with that achieved using traditional microassembly techniques. In microstructure-to-substrate self-assembly of dielectric micromirrors onto MEMS actuators, 150–400-μm-sized components were positioned with accuracy of ±0.2 μm (±0.3° after adhesive curing).[23] Alien Technology Corp. reported accuracy of ±1 μm in the positioning of parts with dimensions of 70–180 μm using fluidic self-assembly;[24] fabrication of MEMS and MOEMS elements with 45° and 90° out-of-plane rotating elements can be accomplished with an accuracy of <0.1°.[21]

5. Self-assembly offers opportunities to achieve low defect rates and high yields. The fabrication of integrated circuits (ICs) and MEMS devices often follows monolithic designs, that is, all components are fabricated in one sequential process. With the increasing complexity of the process flows and the shrinking geometries in each new technology generation, the number of possible sources of yield loss has been increasing.[52]

Self-assembly has the potential to contribute positively to the overall yield in fabrication of functional devices by three mechanisms. First, it allows one to decouple the fabrication of active devices from the fabrication of large-area substrates; the components can then, in principle, be tested *before* assembly so that only fully functional components are used in the final assembly. Second, self-assembly is relatively insensitive to errors in registration. Since misaligned arrays are relatively unstable under the conditions of the assembly, they can break under quasi-equilibrium conditions, giving the components the chance to reassemble correctly. Yields as high as 98–100% have been reported in academic demonstrations of self-assembly based on capillarity.[23,27,53] Third, correction of defects related to missing components in the final aggregates is possible in a second self-assembly step.

6. Self-assembly is a parallel process and can be fast when large numbers of components are involved. We have demonstrated both the fabrication of an electrically functional cylindrical display containing 113 light-emitting diodes (as a first prototype of a cylindrical display) and the generation of a nonplanar array containing ~1600 small silicon cubes (as surrogates of microelectronic devices) by self-assembly (Figure 2c). In both examples, self-assembly (including a defect-correction step) was completed in less than 3 min. Once the components are in contact, self-alignment occurs within a second.[27]

The operational speed that has been achieved in the positioning of micrometer-sized integrated circuits using fluidic self-assembly—more then 2,000,000 per hour—compares favorably with that currently achieved using automated microassembly.[24,54]

Current Problems in Mesoscale Self-Assembly

Self-assembly of mesoscale components seems to offer many advantages to fabrication. It is, however, still an academic subject, and is little used practically. Why? What needs to be done to transform the initial successful demonstrations into a widely practiced, commercially viable technology?

1. Components. The fabrication of the components is probably the most difficult problem that mesoscale self-assembly faces today. The most successful demonstrations of MESA involve *very simple* components: colloids and microspheres (for magnetic materials, photonic crystals, microlenses, and templates). Using self-assembly to make electronic devices will require much more sophisticated components. To achieve maximum density of functionality in a self-assembled device, the individual components have to be smaller than those that can be fabricated currently (optimally, we believe, the sizes of components should be in the range of 1–10 μm), they have to be three-dimensional, *and* they have to be electrically, magnetically, and/or optically functional. Unfortunately, current microfabrication technologies offer no easy ways to fabricate such structures. Several unconventional strategies have been proposed—e.g., folding of prefabricated planar precursors into 3D shapes and self-assembly of planar components onto 3D scaffolds—but at present they are still too complicated to be practical.[18,21]

2. Defects. The level and nature of defects intrinsic to both molecular and mesoscale self-assembly remain to be determined. It is not yet clear what limits the achievable perfection of self-assembling systems: there is no equivalent of thermodynamics or statistical mechanics for these systems. Ultimately, we will need to understand what range of structures can be generated, the relationships between the structures and the numbers of the components, the conditions of self-assembly, and the number of defects that will result.

3. Design. Systematic study of the optimum size, shape, and complexity of the components has been limited by the fact that it is presently impossible to make large numbers of small, complex components. The compromise between *possible* and *optimal* design in the architecture of self-assembled devices also must be defined. It is not yet clear, for example, what 3D structures would best allow the movement of information, the distribution of power, and the efficient removal of heat. Optimum interconnection structure and density, as well as input/output connections to the outside world, must be encoded in the design. It is possible that the architecture of the devices might need to be based on adaptation and redundancy rather than on fail-safe performance.

4. Abiological self-assembly and its characteristics. Much of our current understanding of the process of self-assembly reflects our understanding of molecular systems. The flood of information emerging from biology about self-assembly is a wonderful source of inspiration, but it may limit our imagination. The solutions developed for self-assembly in nature may not be optimal for self-assembly using non-biological components. As one example, magnetic interactions are essentially never used in self-assembly in biology; these interactions—as a result of their insensitivity to many environmental influences such as solvent properties—are among the most promising in MESA.

A fundamental understanding of the particularities and characteristics of self-assembling systems containing micrometer-sized components is still very limited. It is not clear how can one describe the "thermodynamics" and "statistical mechanics" of mesoscale systems containing limited numbers (relative to molecular systems) of components, and where agitation is not thermal. Understanding how to think about the roles of entropy when working with systems containing a small number of components, and how to describe the intrinsic limitations to order in these systems, both remain to be worked out.

Conclusions

The self-assembly of functional aggregates using components larger than molecules is a new approach to "making things," whether materials, devices, or systems. As an area of research, it is still in its infancy, and as an area of technology, it is still mostly a gleam in the eye. Mesoscale self-assembly, however, benefits enormously from the existence proof provided by small, multifunctional systems with complex 3D structures which *are*, indeed, generated by self-assembly: such systems—biological macromolecules, organelles, and cells—form the basis of all life. Nature builds incredibly complex, functional systems, and we can only benefit by extracting the strategies that have evolved in biology and applying them (and other appropriate strategies) in non-biological systems.

Self-assembly of μm- to mm-sized objects has the potential to provide the basis for new technology: (1) it can achieve functionality not accessible using molecules; (2) it can form the basis of a new engineering strategy and provide a simple route to manufacturing 3D structures by replacing robotic assembly of individual parts; and (3) it can, in principle, enable fabrication of *new types of systems* (microelectronics with 3D architectures, conformal and reconfigurable devices such as 3D memory and displays) and *new classes of materials* (heterogeneous, nanoporous, and optical materials, such as photonic crystals, magnetic storage media, and smart surface coatings).[37,55,56]

Mesoscale self-assembly is probably going to be most relevant in the areas of materials and micro- and nanofabrication, but it may have applications elsewhere: in space, where the absence of gravity makes it possible to consider assembling large structures, or in designing systems that are joined by flows of information rather than by materials[57] (for example, self-assembling computer/surveillance networks—a subject of great interest, but one that has not had much contact with molecular self-assembling systems).

The self-assembling systems based on capillary interactions that we have developed are still too primitive to be technologically important or competitive. Our current work in this area is focusing on (1) the development of methods for fabricating the components; (2) analysis of the tradeoff between size, complexity, and functionality of the components; (3) simple demonstrations of functionality that integrate all stages, from fabrication to performance; (4) the identification of specific practical problems that this type of self-assembly can readily solve; and (5) the exploration of advanced biomimetic concepts in the design of these systems.

The exploratory research in mesoscale self-assembly is still far away from self-assembling functional systems that display even a small fraction of the intricate functionality of biological ones, and it cannot yet compete with existing technologies developed for microfabrication. The progression of mesoscale self-assembling systems from fundamental research, through demonstrations of principle, to proofs of concept involving complex functionality, however, has been rapid enough to make us believe that microtechnology and microfabrication will unquestionably benefit from continuing work in the area.

Acknowledgments

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