

Using Self-Assembly for the Fabrication of Nano-Scale Electronic and Photonic Devices

Babak Amir Parviz, *Member, IEEE*, Declan Ryan, and George M. Whitesides

Abstract—Challenges facing the scaling of microelectronics to sub-50 nm dimensions and the demanding material and structural requirements of integrated photonic and microelectromechanical systems suggest that alternative fabrication technologies are needed to produce nano-scale devices. Inspired by complex, functional, self-assembled structures and systems found in Nature we suggest that self-assembly can be employed as an effective tool for nanofabrication. We define a self-assembling system as one in which the elements of the system interact in pre-defined ways to spontaneously generate a higher order structure. Self-assembly is a parallel fabrication process that, at the molecular level, can generate three-dimensional structures with sub-nanometer precision. Guiding the process of self-assembly by external forces and geometrical constraints can reconfigure a system dynamically on demand. We survey some of the recent applications of self-assembly for nanofabrication of electronic and photonic devices. Five self-assembling systems are discussed:

- 1) self-assembled molecular monolayers;
- 2) self-assembly in supramolecular chemistry;
- 3) self-assembly of nanocrystals and nanowires;
- 4) self-assembly of phase-separated block copolymers;
- 5) colloidal self-assembly.

These techniques can generate features ranging in size from a few angstroms to a few microns. We conclude with a discussion of the limitations and challenges facing self-assembly and some potential directions along which the development of self-assembly as a nanofabrication technology may proceed.

Index Terms—Electronic devices, nanofabrication, photonic devices, self-assembled monolayers, self-assembly.

I. INTRODUCTION

THE SCALING of microelectronic devices to sub-50 nm dimensions in recent years has challenged the capability of conventional solid-state microfabrication technologies in the cost-effective, mass production of devices and integrated circuits [1]. Additional architectural and materials requirements imposed on present day solid-state microfabrication technologies by the scaling of photonic devices and microelectromechanical systems (MEMS) call for the study of new methods for nano-scale manufacturing. We identify five key elements that a new nanofabrication technology must satisfy to address the challenges of ever-decreasing dimensions: the technology must

- i) be able to produce components with nanometer (or better) precision;
- ii) be able to assemble systems from these components;

Manuscript received June 16, 2003; revised July 7, 2003. This work was supported by the National Science Foundation (NSF) under Grant CHE-0101432 and the Defense Advanced Research Project Agency (DARPA).

The authors are with the Department of Chemistry and Chemical Biology, Harvard University, Cambridge, MA 02138 USA (e-mail: gwhitesides@gmw-group.harvard.edu).

Digital Object Identifier 10.1109/TADVP.2003.817971

- iii) be parallel in nature—producing many circuits and systems simultaneously;
- iv) be able to structure in three dimensions
- v) be cost-effective.

A number of nanofabrication techniques are under development that take advantage of scanning probe [2], extreme UV [3], e-beam [4], X-ray [5], or ion-beam lithography [6]. These approaches all meet one or a few of the requirements listed above. An alternative approach that has the potential to satisfy many of the above mentioned requirements is self-assembly [7]. The objective of this review is to introduce the concept of self-assembly for nanofabrication and review its recent use in making objects and devices with nano-scale features for electronics and photonics applications.

We define a self-assembling system as one in which the individual components interact in pre-defined ways that result in the spontaneous self-organization of those components into higher-order structures. Self-assembly happens extensively in Nature. From molecules to much more complex biological systems, self-assembly contributes to making patterns, ordered objects, and functional systems. Self-assembly as a nanofabrication method offers a number of advantages.

- 1) Self-assembly is inherently a parallel process. This feature is particularly important at the nano-scale. As the length scale of devices shrink to smaller sizes, it becomes exceedingly difficult to manipulate individual components. Parallel fabrication techniques are also superior to the serial ones in terms of the speed of production.
- 2) Self-assembly at the molecular level can generate structures with sub-nanometer precision.
- 3) Self-assembly at the molecular level offers the ability to generate three-dimensional (3-D) architectures.
- 4) External forces and geometrical constraints can alter the outcome of a self-assembly process. We can take advantage of this fact to re-assemble/re-configure a system dynamically on-demand.

Two main steps are involved in designing a system that takes advantage of self-assembly for fabrication. First, the interaction between the elements that constitute the final system should be tailored for the proper response. The interaction between the elements (molecules, particles) in the system can be controlled using chemistry. Typically, the chemistry involves hydrogen bonding, van der Waals forces, electrostatic forces, or hydrophobic interactions. We note that the internal interaction of the elements does not uniquely define the final state of a self-organizing system. External forces and geometrical constraints can change the outcome of a self-assembly process, and provide flexibility to process designers. The second step in the

design of a self-assembling system is to determine external parameters in order to guide the process and achieve the desired result. For example, electrostatic, magnetic, or hydrodynamic forces can be employed to guide a self-assembly process toward a particular outcome.

In the following sections, we will survey some of the recent applications of self-assembly for making nano-scale features and devices.

II. CURRENT APPLICATIONS OF SELF-ASSEMBLY IN NANOFABRICATION

A. Self-Assembled Monolayers (SAMs) on Solid Substrates

A SAM is a monolayer of organic molecules that forms spontaneously as an ordered lattice on the surface of an appropriate substrate [8]. The molecules in the SAM lattice will chemically bind to the substrate at one end (head group). The other end of the molecules (tail group) constitutes the exposed surface of the SAM. It is possible to form a variety of SAMs, for example, thiols form SAMs on metals such as gold [9], silver, copper, iron [10], platinum [11], and palladium [12]. They can also form on some compound semiconductors, such as InP and GaAs [13]. Although sensitive to moisture in the environment, organosilanes can form SAMs on hydroxylated silicon and silicon dioxide surfaces [14]. Fatty acid molecules will form a SAM on aluminum oxide [15], [16]. Fig. 1 shows a scanning tunneling microscope (STM) image of octanethiol molecules forming a SAM on an atomically flat gold substrate [17].

Changing the tail group of the molecules in the SAM is an easy method to obtain different surface properties. SAMs have been used to render surfaces hydrophobic or hydrophilic [18], and to change the surface states of a semiconductor [19]. In MEMS, SAMs have been employed to reduce the adhesion problem in sacrificial layer release processes [20], to improve the reliability of microactuators, and in sensor structures.

Self-assembly allows for the precise positioning of SAMs, a well defined chemical system, on a target location in a hybrid (molecular-inorganic) device. This characteristic of SAMs makes them good candidates for molecular electronic devices. In most molecular electronic architectures today the inorganic parts of the device such as leads, connections, and a location for the assembly of a SAM are microfabricated and then a SAM is allowed to self-assemble onto the correct location in the device structure. By designing and positioning the proper molecules in the device the desired functionality is obtained. SAMs have been used as molecular memories [21], molecular wires [22], and have exhibited negative differential resistance [23].

Using SAMs to build electronic devices and perhaps eventually circuits is an intriguing prospect. They can potentially provide the basis for very high-density data storage and high-speed devices. It is also interesting to investigate the electro-optical properties of molecular devices. Many organic molecules have signature optical responses especially in the infrared region. It would be beneficial to take advantage of these to make optoelectronic devices.

Wiring a self-assembled molecular device is a major challenge. If the scaling of a technology is limited by the size of the microfabricated structure supporting the nano-scale device, one

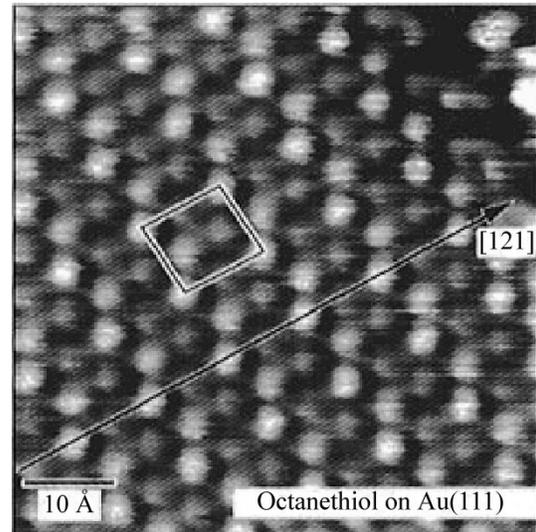


Fig. 1. Scanning tunneling microscopy image of octanethiol monolayer on Au (111). The molecules self-assemble on the gold surface and form the observed ordered lattice spontaneously. Octanethiol molecules commensurate with the underlying gold lattice structure as marked in the image. (Reprinted with permission from [17]. Copyright 1997 American Chemical Society.)

cannot take full advantage of the size reduction offered by using the molecular system. Making a molecule that is more than a single device (wire, resistor, capacitor, transistor, etc.) is necessary to justify the move from conventional crystalline devices to the molecular ones. Most likely, molecular integrated circuits will play an important role in the future of the field.

SAMs provide a number of intriguing opportunities in lithography when used as the resist. They offer unique advantages such as: providing an atomically uniform thickness over a very large area, self-assembling onto substrates with large and uneven surface profiles, and providing a very thin (\sim nm) coating. SAMs have been patterned by microcontact printing [24], scanning probe techniques [25], atom beam [26], e-beam [27], and photolithography [28]. Microcontact printing provides a very simple way for patterning a surface with a molecular monolayer. In this technique [24], a poly(dimethyl siloxane) (PDMS) stamp inked with the molecules is brought into conformal, molecular level contact with the substrate. The molecules transfer from the stamp to the substrate and the pattern of the stamp is replicated on the surface. This method has been used for printing organic electronic circuits [29] and patterning biological materials on substrates [30] as well as patterning curved surfaces [31]. The three outstanding issues in using SAMs as a resist for lithography are levels of defects, lateral diffusion, and post processing. Although wet-etching has been used on patterned SAMs [32], a full library of post-processes are not presently available to fabricate complex architectures.

B. Self-Assembly Using Supramolecular Chemistry

Supramolecular chemistry is a subset of organic and organometallic chemistry that focuses on the assembly of molecular components using non-covalent bonds, e.g., hydrogen bonds, electrostatic bonds [33]–[40]. Supramolecular chemistry, in contrast to two-dimensional self-assembled monolayers, has the ability to fabricate 3-D structures in the size scale

between a single molecule to a few microns. Supramolecular chemistry represents an effort among researchers to fabricate molecular components that will controllably associate to form larger structures, with defined form and functionality, than currently available using covalent bonds. As such we can define molecular recognition as the association of two or more molecules in a predefined way, using non-covalent forces, to form a larger supermolecule [36]. The recognition and specific binding of two complementary DNA strands is an example of such a molecular recognition process.

The opportunity to assemble molecular structures of different size and shape from that allowed by covalent chemistry is illustrated in the formation of aggregates of protein/DNA complexes that self-assemble to form *inter alia* circles, triangles and squares [41] [Fig. 2(a)]. These larger scale molecular structures whose shape can be controlled by experimental conditions demonstrate a route to large (>50 nm) molecular structures.

One elegant demonstration of the potential for new functionality from non-covalent assemblies is the observation of an apparent molecular rotor [42], [43] [Fig. 2(b)]. The rotor is a molecule—hexa-*tert*-butyl decacyclene, HB-DC ($C_{60}H_{66}$), that rotates when it falls out of registry with a close-packed monolayer of HB-dc molecules. The energy required for rotation is less than kT and, consequently, room-temperature operation of this molecular rotor is observed.

Gimzewski and coworkers have reported the direct translation of a molecular recognition event into a nanomechanical response [44]. They fabricated an array of silicon cantilevers and functionalized one side of each cantilever with DNA molecules. When exposed to a solution of complementary DNA molecules, molecular recognition between the DNA strands changed the surface stress, and the cantilevers deflected with a magnitude proportional to the number of bound molecules. This nanomechanical device was capable of detecting a single-base mismatch between two DNA molecules.

It is clear from these examples that using non-covalent bonds to assemble and control molecular form and functionality provides a potential route not only to new materials and phenomena, but also to new applications not accessible using covalent bonds alone.

C. Epitaxially Grown Self-Organized Solid-State Quantum Dots

Molecular beam epitaxy (MBE) and metal-organic vapor phase epitaxy (MOVPE) can produce two-dimensional (2-D) planes of semiconductors with atomic scale precision. These techniques can also be employed to form quantum dots on semiconductor surfaces by relying on the lattice mismatch between alternative layers (Stranski–Krastanow growth mode) [45]. In this growth mode, a thin layer of material (typically a few nanometers) grows epitaxially on a substrate with a different lattice constant. The resultant strain in the deposited layer can initiate a self-reorganization and convert the continuous overlayer into a group of quantum dots. Si/SiGe and (InGa)As/GaAs are the two most widely studied material systems for the self-organized growth of quantum dots using this method. The dot diameter ranges from ten to a few hundred nanometers, with typical dot heights below ten nanometers.

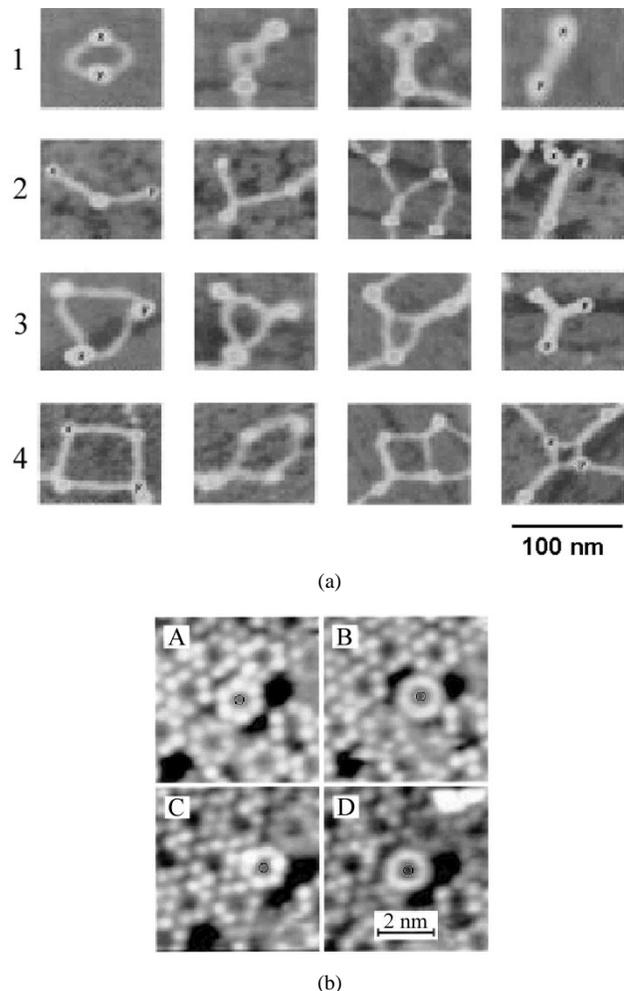


Fig. 2 (a) Atomic force microscopy images of DNA self-assembly: by controlling the ionic strength of the solutions, protein/DNA aggregates of different shapes are formed: 1. rings, 2. trimers, 3. triangular, and 4. square. (b) Scanning tunneling microscopy image of a sub-monolayer of hexa-*tert*-butyl decacyclene molecules on a Cu(100) surface in ultrahigh vacuum at room temperature: (A), (C) an individual HB-DC molecule is imaged as a six-lobed structure in registry with neighboring molecules and (B), (D) the same molecule is imaged as a torus when its position is not registered with neighboring molecules—the toroidal shape is a result of the rotation of the molecule at speeds greater than the scan rate used for imaging. [(a) reprinted with permission from [41]. Copyright 2001. (b) reprinted with permission from [42]. Copyright 1998 American Association for the Advancement of Science.]

Varying the substrate temperature during growth, the substrate angle, the flux ratios, the lattice mismatch, and the growth rate can tune the self-assembly of the dots on the surface [46], [47]. This has allowed for close control of the dot size and distribution and also the average spacing between adjacent dots; forming long range ordered lattices of these dots has not, however, been achieved to date. Patterned substrates with step edges, grooves, and stress concentration locations have been used to guide the growth of the dots [48]. A buffer layer between stacks of dots has been used to influence the vertical alignment of the dots [49].

D. Self-Assembly of Nanocrystals and Nanowires

Chemical synthesis can provide an alternative to MBE in a number of areas. A diverse range of shapes, sizes and, consequently, new material properties are accessible using chemistry

[50]–[55]. Nanocrystals of various metals and semiconductors, nanowires, and even highly asymmetric shapes [56]–[58] such as teardrops and tetrapods [59] are some of the nano-scale objects that can be made using chemical synthesis (Fig. 3). While interest in individual nanocrystals and nanowires is driven toward an understanding of the size- and shape-dependent properties of various materials, the collective properties of assemblies of these objects is technologically relevant [52], [60]–[66].

Through judicious choice of the surface chemistry of nanocrystals, it is possible to allow a dispersion of nanocrystals to self-organize and form ordered two-dimensional or 3-D superlattices [64]. The interaction driving this organization process is predominantly Van der Waals attraction between nanocrystals. It is possible to control the electronic coupling between arrays of semiconductor and metal nanocrystals by changing the spacing between individual nanocrystals in a superlattice. In the case of close-packed 3-nm silver nanocrystals, an insulator-to-metal transition occurs as a function of the separation between nanocrystals when the ratio of the diameter to interparticle separation approaches 1.2 [67]. This transition is a result of the mode of electron transmission between individual nanocrystals switching from tunneling (and hopping) to coherent transport.

A candidate for high-density data storage media is a self-organized array of magnetic FePt nanocrystals [68]. Magnetic FePt nanocrystals, upon thermal annealing, undergo a phase transformation to yield a face-centered tetragonal superlattice. This superlattice structure is particularly useful for data storage applications, as the collective property associated with this structure is high coercivity. Such thin nanocrystal films have the potential to provide Tbit/in² storage densities.

The prevalence of self-assembled structures in biological systems has inspired researchers to borrow biological concepts when fashioning new approaches to fabricating self-assembled arrays of nanostructures. Alivisatos and Mirkin have modified gold nanocrystals with complementary strands of DNA [69], [70]. When mixed together, the gold nanocrystals recognize each other using the specific biochemistry of DNA to form mixtures of dimer (two nanocrystals) and trimer (three nanocrystals) aggregates. Belcher and coworkers have reported the formation of a liquid crystalline phase of virus material where each virus has a semiconductor nanocrystal tethered at one of its ends [71], [72]. The observation of liquid crystalline behavior provides a demonstration of new material properties emerging at the interface between materials and biological sciences. Metal nanowires have also been synthesized using the structure of a linear virus as a template for metal growth [73].

Compared to nanocrystals, the assembly of nanowire arrays is more challenging due to the shape anisotropy of the object [55], [74]. Nanowire self-assembly generally results in short to medium range superlattices with only partial order. Several groups have presented methods to address this difficulty including the assembly of nanowire structures using microfluidic channels [75] and electric-field assisted assembly [76]. A field-effect transistor based on an assembly of crossed semiconductor nanowires was demonstrated using fluidic alignment [77], [78]. Recently, Alivisatos and coworkers have demonstrated liquid crystalline phases of semiconductor CdSe nanorods [79]. The

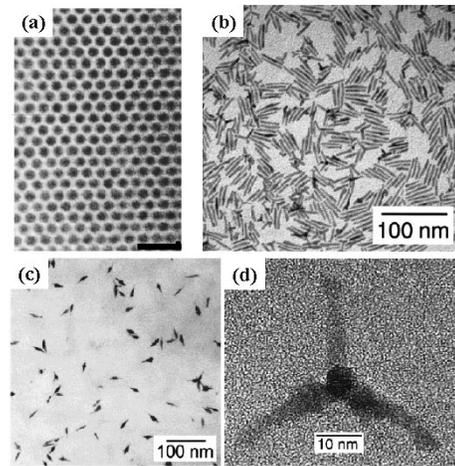


Fig. 3. Transmission electron micrographs of CdSe nanocrystals of different shapes: (a) Close-packed array of 4.8 nm diameter nanocrystals (scalebar = 20 nm), (b) rodlike CdSe nanocrystals with an average length of 34.5 nm and an aspect ratio of 10:1, (c) teardrop shape nanocrystals, and (d) tetrapod shaped nanocrystal with its fourth axis pointing out of the plane. (Copyright 2000 American Chemical Society.)

nanorods, due to their anisotropic shape, align with a high degree of directional order upon solvent evaporation and exhibit birefringence. The resulting nanorod assembly may find applications in electro-optical devices such as polarizing light emitting diodes.

The use of one-dimensional semiconductor materials as candidate laser materials has attracted significant attention because of the possibility of improved excitonic recombination due to carrier confinement. Lieber and coworkers have demonstrated an electrically pumped CdS nanowire laser [80]. Chemically grown semiconductor nanowires can act as Fabry–Perot resonators after cleavage of both ends of the nanowire. This device consisted of an n-type CdS nanowire resting on a p-type Si substrate with a metal/alumina film evaporated on top of the nanowire. Carrier recombination in this p-n junction resulted in nanowire electroluminescence. Other nanocrystal and nanowire optoelectronic phenomena reported include electrogenerated silicon nanocrystal luminescence [81], optically pumped semiconductor nanowire lasers [82], and electrochromic semiconductor nanocrystals [83].

E. Self-Assembly of Block Copolymers

Block copolymers are polymers with chains that consist of distinct sections (blocks) each containing only one type of monomer. If the blocks in the polymer chain are incompatible and do not mix, the polymer can self-assemble into ordered microdomains [84]–[86] (Fig. 4). Self-assembly is a result of microphase separation and de-mixing of various parts of the polymer. The resultant microdomains in the polymer structure consist of different types of monomer. The size of each microdomain depends on the preparation method, chain length, polymer type, volume fraction of each component, and temperature, and is typically between 10 nm to 100 nm. Block copolymers can self-assemble into cylinders, lamellae, and spheres, among other shapes. These shapes can have aspect ratios exceeding 50:1 [87]. Such aspect ratios are difficult to

attain with conventional microfabrication techniques in the direction perpendicular to the surface of the wafer.

By taking advantage of self-assembly in block copolymers, one can form nano-scale patterns on the surface or in the bulk of the material. Self-assembly of thin films of block copolymers on surfaces into ordered patterns has been studied extensively. After the ordered pattern of polymer self-assembles on a surface, by selectively removing one phase of the polymer, the resulting polymer pattern can be transferred to the substrate by various methods such as dry etching or electroplating. For example, the self-assembly of polystyrene (PS)/poly(methylmethacrylate) PMMA in the shape of cylinders perpendicular to a gold surface has been used for the fabrication of nanoelectrodes [87]. In this case, the PMMA cylinders were removed after exposure to the UV light, leaving behind a hexagonal pattern of gold nanoelectrodes. Bulk self-assembly of the block copolymers into micro-spherical domains [88] has been studied for making photonic crystals and mechanochromic materials. The polymers can also be mixed with inorganic nanocrystals and molecules such as fullerene to provide an extra degree of freedom for engineering the properties of the final superlattice [89].

Block copolymers provide an easy route to form ordered patterns with nano-scale features on a surface. Many of the polymers are commercially available and inexpensive. Although short range order has been demonstrated for a number of block copolymer systems, achieving long range order remains an elusive goal.

F. Colloidal Self-Assembly

The self-assembly of 100–1000 nm diameter micro-spheres into ordered arrays have been extensively studied, particularly as a means to fabricate photonic bandgap crystals [90]. These colloidal photonic band gap crystals can be used in lasers [91] and waveguides [92]. SiO₂, ZnO, or polymer spheres with diameters ranging from a 100 nm to a few microns have been caused to pack under the influence of capillary forces, and make ordered lattices [93]–[95]. The packing process can be controlled by gravity, convection, changing the surface chemistry of the spheres, or imposing geometrical constraints on the system. For example, by assembling a lattice of spheres inside a microchannel, it is possible to fabricate lines and 3-D patterns with internal feature sizes smaller than is allowed by photolithography [96], [97]. The space between the spheres can be filled with other materials such as carbon, CdSe, and metal oxides [98], [99]. The filling process can be accomplished by sintering nanocrystals, electrodeposition, chemical vapor deposition, or oxide reduction. It is also possible to remove the spheres after the refill process and produce a porous structure with nano-scale ordered voids [100].

A hierarchical self-assembly process has been developed by Yang and coworkers [101] that uses porous oxides as the filling material between the spheres. In this case, the self-assembly process allows for the controlled formation of ordered patterns over three orders of magnitude of the length scale. The diameter of the pores in the metal oxide used to infiltrate the lattice is on the order of 10 nm. The ordered pores in the metal oxide result from mixing the precursor for the metal oxide with a block copolymer and subsequently removing the polymer phase. The

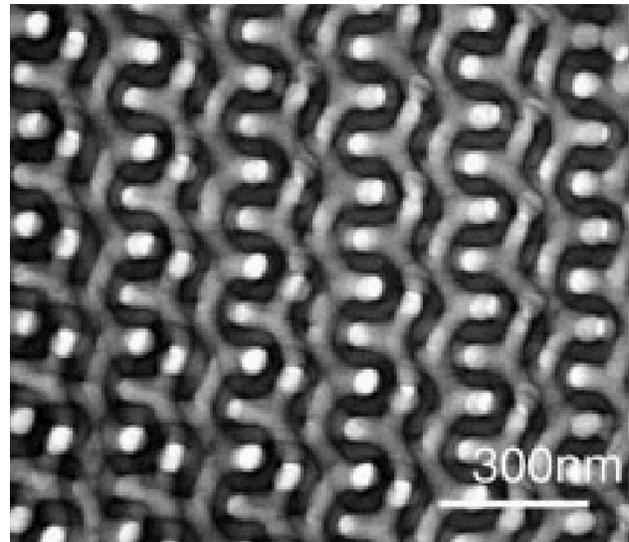


Fig. 4. Transmission electron micrograph of OsO₄-stained cryo-microtomed section of self-assembled styrene/isoprene block copolymer. The lattice constant for this architecture is about 250 nm. The styrene networks appear light in this image. (Reprinted with permission from [86]. Copyright 2002.)

porous metal oxide fills the space between a self-assembled lattice of spheres with a diameter of about 100 nm. The self-assembly process of the spheres is controlled by the pattern of microchannels with a length scale larger than 1000 nm. Fig. 5 shows examples of structures made by this technique. It is noteworthy that hierarchical self-assembly can controllably create shapes with nano-scale features in the desired locations. Making these nano-scale features is not limited by the capabilities of photolithography.

G. Directed Self-Assembly

Self-assembly, as described thus far, produces structures from components that organize among themselves in a defined manner. As mentioned above, the application of external forces and constraints can alter/control the outcome of a self-assembly process. In this regard, we introduce directed self-assembly as the ability to control the organization of individual components using methods supplementary to the original interactions driving self-assembly. Directed self-assembly can, therefore, provide not only the ability to tune the interaction between individual assembling components but also the ability to position the final assembly at a desired location. For example, electric-field assisted self-assembly is used to position nanowires on a pad [76] or to control the orientation of self-assembled patterns in a block copolymer blend [102]. By varying the geometrical constraints on a set of assembling colloidal particles in a microchannel, different packing orders are obtained [103]. The structure of photonic crystals consisting of magnetic particles can be tuned by the application of an external magnetic field [104].

III. CHALLENGES AND LIMITATIONS OF SELF-ASSEMBLY

Due to thermal fluctuations and the statistical nature of self-assembly in the nano-scale, we anticipate the presence of a finite

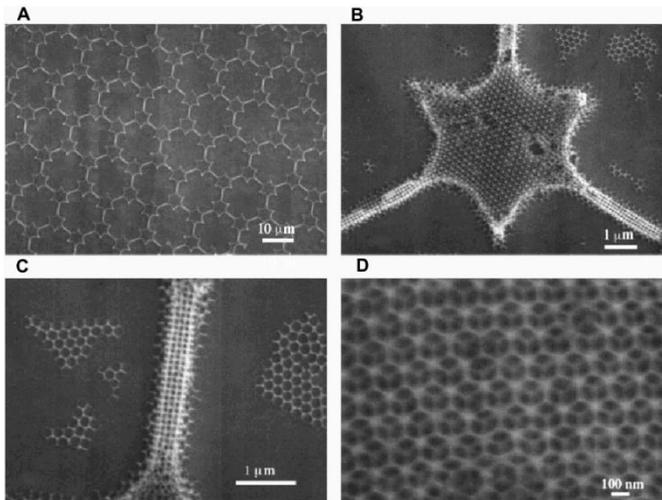


Fig. 5. Scanning electron microscopy images of hierarchical colloidal self-assembly. (A) The largest pattern in the structure is made by using micro-channels. (B) Latex micro-spheres self-assemble in the channels to form a 3-D lattice structure. A close up is shown in (C). (D) The spacing between the silica spheres are filled with a porous oxide and then the spheres are removed from the structure. (Reprinted with permission from [101]. Copyright 1998 American Association for the Advancement of Science.)

number of defects in the final assembled structures. Some macroscopic phenomenon such as wettability are less sensitive to defects in a self-assembled molecular monolayer, however, almost perfect yields are required to operate a molecular electronic device. Investigating architectures that are tolerant to imperfections and defects will be essential for designing a system that takes advantage of self-assembly. Most of the self-assembling systems at present generate repetitive patterns with short to medium range order. Working within these constraints is another challenge for designers of device and system architectures. Designing and making the components for self-assembly may not be a trivial task. For example, making an elementary molecular circuit that can self-assemble into a larger system with more complexity than the starting elements, poses a major challenge when beginning to design and synthesize the molecular components.

IV. CONCLUSION

Self-assembly plays a prominent role in making objects, patterns, and functional systems in Nature. By presenting highly complex, functional systems with nano-scale components, biology certainly exhibits the best manifestation of self-assembly. Inspired by this impressive demonstration in Nature, we argue that self-assembly has the potential to radically alter how we generate nano-scale components and how we assemble these components into larger systems.

Several approaches for using self-assembly for nanofabrication are already under investigation. They range from molecular manipulation through the use of SAMs and supramolecular chemistry, to much larger systems made by the controlled self-assembly of colloids. The products of these self-assembly techniques can be used either directly in a device (for example, a SAM in a molecular electronics device), or indirectly to assist conventional microfabrication processes (for example, transfer of a pattern made in phase-separated block copolymers to a sub-

strate with reactive ion etching). In the near future, we anticipate a hybrid approach, combining microfabrication with nanofabrication through self-assembly, to be the dominant method for making devices and systems by self-assembly. The ability to make an entire system exclusively using self-assembly remains to be seen.

Self-assembly allows for the integration of incompatible process technologies. For example, single nanowire lasers can self-assemble on a variety of substrates. This flexibility provides a way for the integration of optical and electronic devices on multiple platforms. The study of self-assembly also paves the way for investigating two other very interesting self-processes, namely, self-healing and self-replication.

Self-assembly has been employed to make molecular electronic devices, memories, and photonic bandgap materials in research labs; for the most part however, it remains a research tool. Although it is expected that self-assembly will be a cost effective and efficient method for manufacturing nano-scale devices and systems, self-assembly will remain an unknown entity as a commercial process until a functional device is realized in a commercial scenario. The study of defects in self-assembling systems and introducing defect tolerant architectures will play a prominent role in transferring self-assembly from research laboratories to device manufacturing.

The engineering and scientific enthusiasm for challenges related to self-assembly continues to grow and justifiably so. We anticipate developments toward the integration of self-assembled structures in existing microfabricated systems, an increased interest in mimicking biological function to produce complex structures, and the broad participation of multiple disciplines in addressing some of the challenges currently facing self-assembly. Self-assembly, we believe, will be a central approach to nanofabrication in future.

REFERENCES

- [1] M. T. Bohr, "Nanotechnology goals and challenges for electronic applications," *IEEE Trans. Nanotechnol.*, vol. 1, pp. 56–62, Mar. 2002.
- [2] C. A. Mirkin, S. H. Hong, and L. Demers, "Dip-pen nanolithography: controlling surface architecture on the sub-100 nanometer length scale," *ChemPhysChem*, vol. 2, pp. 37–39, 2001.
- [3] J. P. H. Benschop, A. J. J. Van Dijsseldonk, W. M. Kaiser, and D. C. Ockwell, "EUCLIDES: European EUV lithography milestones," *Solid State Technol.*, vol. 42, pp. 43–44, 1999.
- [4] J. G. Chase and B. W. Smith, "Overview of modern lithography techniques and a MEMS-based approach to high throughput rate electron beam lithography," *J. Intell. Mater. Syst. Structures*, vol. 12, pp. 807–817, 2001.
- [5] F. Cerrina, "X-ray imaging: applications to patterning and lithography," *J. Phys. D (Appl. Phys.)*, vol. 33, pp. R103–R116, 2000.
- [6] J. Melngailis, A. A. Mondelli, I. L. Berry III, and R. Mohondro, "A review of ion projection lithography," *J. Vacuum Sci. Technol. B (Microelectron. Nanometer Structures)*, vol. 16, pp. 927–957, 1998.
- [7] G. M. Whitesides and B. Grzybowski, "Self-assembly at all scales," *Science*, vol. 295, pp. 2418–2421, 2002.
- [8] A. Ulman, "Formation and structure of self-assembled monolayers," *Chem. Rev.*, vol. 96, pp. 1533–1554, 1996.
- [9] P. E. Laibinis, G. M. Whitesides, D. L. Allara, Y. T. Tao, A. N. Parikh, and R. G. Nuzzo, "Comparison of the structures and wetting properties of self-assembled monolayers of normal-alkanethiols on the coinage metal-surfaces Cu, Ag, Au," *J. Amer. Chem. Soc.*, vol. 113, pp. 7152–7167, 1991.
- [10] M. Volmer, M. Stratmann, and H. Viehhaus, "Electrochemical and electron spectroscopic investigations of iron surfaces modified with thiols," *Surf. Interface Anal.*, vol. 16, pp. 278–282, 1990.

- [11] K. Shimazu, Y. Sato, I. Yagi, and K. Uosaki, "Packing state and stability of self-assembled monolayers of 11-ferrocenyl-1-undecanethiol on platinum-electrodes," *Bull. Chem. Soc. Jpn.*, vol. 67, pp. 863–865, 1994.
- [12] J. C. Love, D. B. Wolfe, R. Haasch, M. L. Chabiny, K. E. Paul, G. M. Whitesides, and R. G. Nuzzo, "Formation and structure of self-assembled monolayers of alkanethiols on palladium," *J. Amer. Chem. Soc.*, vol. 125, pp. 2597–2609, 2003.
- [13] C. W. Sheen, J. X. Shi, J. Martensson, A. N. Parikh, and D. L. Allara, "A new class of organized self-assembled monolayers—alkane thiols on GaAs(100)," *J. Amer. Chem. Soc.*, vol. 114, pp. 1514–1515, 1992.
- [14] J. D. Legrange, J. L. Markham, and C. R. Kurkjian, "Effects of surface hydration on the deposition of silane monolayers on silica," *Langmuir*, vol. 9, pp. 1749–1753, 1993.
- [15] D. L. Allara and R. G. Nuzzo, "Spontaneously organized molecular assemblies .1. Formation, dynamics, and physical-properties of normal-alkanoic acids adsorbed from solution on an oxidized aluminum surface," *Langmuir*, vol. 1, pp. 45–52, 1985.
- [16] ———, "Spontaneously organized molecular assemblies .2. Quantitative infrared spectroscopic determination of equilibrium structures of solution-adsorbed normal-alkanoic acids on an oxidized aluminum surface," *Langmuir*, vol. 1, pp. 52–66, 1985.
- [17] G. E. Poirier, "Characterization of organosulfur molecular monolayers on Au(111) using scanning tunneling microscopy," *Chem. Rev.*, vol. 97, pp. 1117–1127, 1997.
- [18] N. L. Abbott, J. P. Folkers, and G. M. Whitesides, "Manipulation of the wettability of surfaces on the 0.1-micrometer to 1-micrometer scale through micromachining and molecular self-assembly," *Science*, vol. 257, pp. 1380–1382, 1992.
- [19] M. Bollani, R. Piagge, and D. Narducci, "Modulation of Si(100) electronic surface density due to supramolecular interactions of gaseous molecules with self-assembled organic monolayers," *Mater. Sci. Eng. C-Biomimetic Supramol. Syst.*, vol. 15, pp. 253–255, 2001.
- [20] W. R. Ashurst, C. Yau, C. Carraro, R. Maboudian, and M. T. Dugger, "Dichlorodimethylsilane as an anti-stiction monolayer for MEMS: a comparison to the octadecyltrichlosilane self-assembled monolayer," *J. Microelectromech. Syst.*, vol. 10, pp. 41–49, 2001.
- [21] Q. L. Li, G. Mathur, M. Homs, S. Surthi, V. Misra, V. Malinovsky, K. H. Schweikart, L. H. Yu, J. S. Lindsey, Z. M. Liu, R. B. Dabke, A. Yasser, D. F. Bocian, and W. G. Kuhr, "Capacitance and conductance characterization of ferrocene-containing self-assembled monolayers on silicon surfaces for memory applications," *Appl. Phys. Lett.*, vol. 81, pp. 1494–1496, 2002.
- [22] S. Hong, R. Reifenger, W. Tian, S. Datta, J. I. Henderson, and C. P. Kubiak, "Molecular conductance spectroscopy of conjugated, phenyl-based molecules on Au(111): the effect of end groups on molecular conduction," *Superlattices Microstruct.*, vol. 28, pp. 289–303, 2000.
- [23] C. B. Gorman, R. L. Carroll, and R. R. Fuierer, "Negative differential resistance in patterned electroactive self-assembled monolayers," *Langmuir*, vol. 17, pp. 6923–6930, 2001.
- [24] J. L. Wilbur, A. Kumar, E. Kim, and G. M. Whitesides, "Microfabrication by microcontact printing of self-assembled monolayers," *Adv. Mater.*, vol. 6, pp. 600–604, 1994.
- [25] G. Y. Liu, S. Xu, and Y. L. Qian, "Nanofabrication of self-assembled monolayers using scanning probe lithography," *Accounts Chem. Res.*, vol. 33, pp. 457–466, 2000.
- [26] K. K. Berggren, A. Bard, J. L. Wilbur, J. D. Gillaspay, A. G. Helg, J. J. McClelland, S. L. Rolston, W. D. Phillips, M. Prentiss, and G. M. Whitesides, "Microlithography by using neutral metastable atoms and self-assembled monolayers," *Science*, vol. 269, pp. 1255–1257, 1995.
- [27] M. J. Lercel, H. G. Craighead, A. N. Parikh, K. Seshadri, and D. L. Allara, "Sub-10 nm lithography with self-assembled monolayers," *Appl. Phys. Lett.*, vol. 68, pp. 1504–1506, 1996.
- [28] S. Q. Sun and G. J. Leggett, "Generation of nanostructures by scanning near-field photolithography of self-assembled monolayers and wet chemical etching," *Nano Lett.*, vol. 2, pp. 1223–1227, 2002.
- [29] J. A. Rogers, Z. Bao, M. Meier, A. Dodabalapur, O. J. A. Schueller, and G. M. Whitesides, "Printing, molding, and near-field photolithographic methods for patterning organic lasers, smart pixels and simple circuits," *Synth. Met.*, vol. 115, pp. 5–11, 2000.
- [30] G. M. Whitesides, E. Ostuni, S. Takayama, X. Y. Jiang, and D. E. Ingber, "Soft lithography in biology and biochemistry," *Annu. Rev. Biomed. Eng.*, vol. 3, pp. 335–373, 2001.
- [31] R. J. Jackman, J. L. Wilbur, and G. M. Whitesides, "Fabrication of sub-micrometer features on curved substrates by microcontact printing," *Science*, vol. 269, pp. 664–666, 1995.
- [32] A. Kumar and G. M. Whitesides, "Features of gold having micrometer to centimeter dimensions can be formed through a combination of stamping with an elastomeric stamp and an alkanethiol ink followed by chemical etching," *Appl. Phys. Lett.*, vol. 63, pp. 2002–2004, 1993.
- [33] J. M. Lehn, "From molecular to supramolecular chemistry—science, art and industry," *Interdiscip. Sci. Rev.*, vol. 10, pp. 72–85, 1985.
- [34] ———, "Supramolecular chemistry—receptors, catalysts, and carriers," *Science*, vol. 227, pp. 849–856, 1985.
- [35] ———, "Supramolecular chemistry—scope and perspectives molecules, supermolecules, and molecular devices," *Angew. Chem.-Int. Edit. Engl.*, vol. 27, pp. 89–112, 1988.
- [36] ———, "Perspectives in supramolecular chemistry—from molecular recognition toward molecular information-processing and self-organization," *Angew. Chem.-Int. Edit. Engl.*, vol. 29, pp. 1304–1319, 1990.
- [37] ———, "Supramolecular chemistry," *Science*, vol. 260, pp. 1762–1763, 1993.
- [38] M. Gomez-Lopez and J. F. Stoddart, "A review of molecular and supramolecular switching systems," *Bull. Soc. Chim. Belg.*, vol. 106, pp. 491–500, 1997.
- [39] M. Gomez-Lopez, J. A. Preece, and J. F. Stoddart, "The art and science of self-assembling molecular machines," *Nanotechnology*, vol. 7, pp. 183–192, 1996.
- [40] P. A. Gale, "Supramolecular chemistry: from complexes to complexity," *Philos. Trans. R. Soc. Lond. Ser. A-Math. Phys. Eng. Sci.*, vol. 358, pp. 431–453, 2000.
- [41] C. M. Niemeyer, M. Adler, S. Lenhart, S. Gao, H. Fuchs, and L. F. Chi, "Nucleic acid supercoiling as a means for ionic switching of DNA-nanoparticle networks," *ChemBiochem*, vol. 2, pp. 260–264, 2001.
- [42] J. K. Gimzewski, C. Joachim, R. R. Schlittler, V. Langlais, H. Tang, and I. Johansson, "Rotation of a single molecule within a supramolecular bearing," *Science*, vol. 281, pp. 531–533, 1998.
- [43] C. Joachim and J. K. Gimzewski, "Single molecular rotor at the nanoscale," *Molecular Mach. Motors*, vol. 99, pp. 1–18, 2001.
- [44] J. Fritz, M. K. Baller, H. P. Lang, H. Rothuizen, P. Vettiger, E. Meyer, H. J. Guntherodt, C. Gerber, and J. K. Gimzewski, "Translating biomolecular recognition into nanomechanics," *Science*, vol. 288, pp. 316–318, 2000.
- [45] R. Notzel, "Self-organized growth of quantum-dot structures," *Semicond. Sci. Technol.*, vol. 11, pp. 1365–1379, 1996.
- [46] G. S. Solomon, J. A. Trezza, and J. S. Harris, "Effects of monolayer coverage, flux ratio, and growth-rate on the island density of InAs islands on GaAs," *Appl. Phys. Lett.*, vol. 66, pp. 3161–3163, 1995.
- [47] ———, "Substrate-temperature and monolayer coverage effects on epitaxial ordering of InAs and InGaAs islands on GaAs," *Appl. Phys. Lett.*, vol. 66, pp. 991–993, 1995.
- [48] K. H. Ploog and R. Notzel, "Novel semiconductor nanostructures by functional self-organized epitaxy," *Physica E*, vol. 11, pp. 78–88, 2001.
- [49] Q. H. Xie, A. Madhukar, P. Chen, and N. P. Kobayashi, "Vertically self-organized InAs quantum box islands on GaAs(100)," *Phys. Rev. Lett.*, vol. 75, pp. 2542–2545, 1995.
- [50] A. P. Alivisatos, "Semiconductor clusters, nanocrystals, and quantum dots," *Science*, vol. 271, pp. 933–937, 1996.
- [51] J. R. Heath and J. J. Shiang, "Covalency in semiconductor quantum dots," *Chem. Soc. Rev.*, vol. 27, pp. 65–71, 1998.
- [52] G. Markovich, C. P. Collier, S. E. Henrichs, F. Remacle, R. D. Levine, and J. R. Heath, "Architectonic quantum dot solids," *Accounts Chem. Res.*, vol. 32, pp. 415–423, 1999.
- [53] C. M. Lieber, "One-dimensional nanostructures: chemistry, physics & applications," *Solid State Commun.*, vol. 107, pp. 607–616, 1998.
- [54] C. B. Murray, S. H. Sun, W. Gaschler, H. Doyle, T. A. Betley, and C. R. Kagan, "Colloidal synthesis of nanocrystals and nanocrystal superlattices," *IBM J. Res. Dev.*, vol. 45, pp. 47–56, 2001.
- [55] Y. N. Xia, P. D. Yang, Y. G. Sun, Y. Y. Wu, B. Mayers, B. Gates, Y. D. Yin, F. Kim, and Y. Q. Yan, "One-dimensional nanostructures: synthesis, characterization, and applications," *Adv. Mater.*, vol. 15, pp. 353–389, 2003.
- [56] M. Li, H. Schnablegger, and S. Mann, "Coupled synthesis and self-assembly of nanoparticles to give structures with controlled organization," *Nature*, vol. 402, pp. 393–395, 1999.
- [57] V. F. Puentes, D. Zanchet, C. K. Erdonmez, and A. P. Alivisatos, "Synthesis of hcp-Co nanodisks," *J. Amer. Chem. Soc.*, vol. 124, pp. 12 874–12 880, 2002.
- [58] G. S. Metraux, Y. C. Cao, R. C. Jin, and C. A. Mirkin, "Triangular nanoframes made of gold and silver," *Nano Lett.*, vol. 3, pp. 519–522, 2003.

- [59] L. Manna, E. C. Scher, and A. P. Alivisatos, "Synthesis of soluble and processable rod-, arrow-, teardrop-, and tetrapod-shaped CdSe nanocrystals," *J. Amer. Chem. Soc.*, vol. 122, pp. 12 700–12 706, 2000.
- [60] C. B. Murray, C. R. Kagan, and M. G. Bawendi, "Self-organization of Cdse nanocrystallites into 3-dimensional quantum-dot superlattices," *Science*, vol. 270, pp. 1335–1338, 1995.
- [61] C. R. Kagan, C. B. Murray, and M. G. Bawendi, "Long-range resonance transfer of electronic excitations in close-packed CdSe quantum-dot solids," *Phys. Rev. B*, vol. 54, pp. 8633–8643, 1996.
- [62] C. P. Collier, R. J. Saykally, J. J. Shiang, S. E. Henrichs, and J. R. Heath, "Reversible tuning of silver quantum dot monolayers through the metal-insulator transition," *Science*, vol. 277, pp. 1978–1981, 1997.
- [63] C. P. Collier, T. Vossmeier, and J. R. Heath, "Nanocrystal superlattices," *Annu. Rev. Phys. Chem.*, vol. 49, pp. 371–404, 1998.
- [64] C. B. Murray, C. R. Kagan, and M. G. Bawendi, "Synthesis and characterization of monodisperse nanocrystals and close-packed nanocrystal assemblies," *Annu. Rev. Mater. Sci.*, vol. 30, pp. 545–610, 2000.
- [65] V. Russier, C. Petit, J. Legrand, and M. P. Pileni, "Collective magnetic properties of cobalt nanocrystals self-assembled in a hexagonal network: theoretical model supported by experiments," *Phys. Rev. B*, vol. 62, pp. 3910–3916, 2000.
- [66] M. P. Pileni, "Nanocrystal self-assemblies: fabrication and collective properties," *J. Phys. Chem. B*, vol. 105, pp. 3358–3371, 2001.
- [67] G. Markovich, C. P. Collier, and J. R. Heath, "Reversible metal-insulator transition in ordered metal nanocrystal monolayers observed by impedance spectroscopy," *Phys. Rev. Lett.*, vol. 80, pp. 3807–3810, 1998.
- [68] S. H. Sun, C. B. Murray, D. Weller, L. Folks, and A. Moser, "Monodisperse FePt nanoparticles and ferromagnetic FePt nanocrystal superlattices," *Science*, vol. 287, pp. 1989–1992, 2000.
- [69] A. P. Alivisatos, K. P. Johnsson, X. G. Peng, T. E. Wilson, C. J. Loweth, M. P. Bruchez, and P. G. Schultz, "Organization of 'nanocrystal molecules' using DNA," *Nature*, vol. 382, pp. 609–611, 1996.
- [70] C. A. Mirkin, R. L. Letsinger, R. C. Mucic, and J. J. Storhoff, "A DNA-based method for rationally assembling nanoparticles into macroscopic materials," *Nature*, vol. 382, pp. 607–609, 1996.
- [71] S. W. Lee, C. B. Mao, C. E. Flynn, and A. M. Belcher, "Ordering of quantum dots using genetically engineered viruses," *Science*, vol. 296, pp. 892–895, 2002.
- [72] S. R. Whaley, D. S. English, E. L. Hu, P. F. Barbara, and A. M. Belcher, "Selection of peptides with semiconductor binding specificity for directed nanocrystal assembly," *Nature*, vol. 405, pp. 665–668, 2000.
- [73] E. Dujardin, C. Peet, G. Stubbs, J. N. Culver, and S. Mann, "Organization of metallic nanoparticles using tobacco mosaic virus templates," *Nano Lett.*, vol. 3, pp. 413–417, 2003.
- [74] Y. Y. Wu, H. Q. Yan, M. Huang, B. Messer, J. H. Song, and P. D. Yang, "Inorganic semiconductor nanowires: rational growth, assembly, and novel properties," *Chem.-Eur. J.*, vol. 8, pp. 1261–1268, 2002.
- [75] Y. Huang, X. F. Duan, Q. Q. Wei, and C. M. Lieber, "Directed assembly of one-dimensional nanostructures into functional networks," *Science*, vol. 291, pp. 630–633, 2001.
- [76] P. A. Smith, C. D. Nordquist, T. N. Jackson, T. S. Mayer, B. R. Martin, J. Mbindyo, and T. E. Mallouk, "Electric-field assisted assembly and alignment of metallic nanowires," *Appl. Phys. Lett.*, vol. 77, pp. 1399–1401, 2000.
- [77] Y. Huang, X. F. Duan, Y. Cui, L. J. Lauhon, K. H. Kim, and C. M. Lieber, "Logic gates and computation from assembled nanowire building blocks," *Science*, vol. 294, pp. 1313–1317, 2001.
- [78] X. F. Duan, Y. Huang, and C. M. Lieber, "Nonvolatile memory and programmable logic from molecule-gated nanowires," *Nano Lett.*, vol. 2, pp. 487–490, 2002.
- [79] L. S. Li, J. Walda, L. Manna, and A. P. Alivisatos, "Semiconductor nanorod liquid crystals," *Nano Lett.*, vol. 2, pp. 557–560, 2002.
- [80] X. F. Duan, Y. Huang, R. Agarwal, and C. M. Lieber, "Single-nanowire electrically driven lasers," *Nature*, vol. 421, pp. 241–245, 2003.
- [81] Z. F. Ding, B. M. Quinn, S. K. Haram, L. E. Pell, B. A. Korgel, and A. J. Bard, "Electrochemistry and electrogenerated chemiluminescence from silicon nanocrystal quantum dots," *Science*, vol. 296, pp. 1293–1297, 2002.
- [82] M. H. Huang, S. Mao, H. Feick, H. Q. Yan, Y. Y. Wu, H. Kind, E. Weber, R. Russo, and P. D. Yang, "Room-temperature ultraviolet nanowire nanolasers," *Science*, vol. 292, pp. 1897–1899, 2001.
- [83] C. J. Wang, M. Shim, and P. Guyot-Sionnest, "Electrochromic nanocrystal quantum dots," *Science*, vol. 291, pp. 2390–2392, 2001.
- [84] G. Krausch and R. Magerle, "Nanostructured thin films via self-assembly of block copolymers," *Adv. Mater.*, vol. 14, pp. 1579–, 2002.
- [85] G. Krausch, "Surface-induced self-assembly in thin polymer-films," *Mater. Sci. Eng. R-Rep.*, vol. 14, pp. 1–94, 1995.
- [86] A. M. Urbas, M. Maldovan, P. DeRege, and E. L. Thomas, "Bicontinuous cubic block copolymer photonic crystals," *Adv. Mater.*, vol. 14, pp. 1850–1853, 2002.
- [87] E. Jeoung, T. H. Galow, J. Schotter, M. Bal, A. Ursache, M. T. Tuominen, C. M. Stafford, T. P. Russell, and V. M. Rotello, "Fabrication and characterization of nanoelectrode arrays formed via block copolymer self-assembly," *Langmuir*, vol. 17, pp. 6396–6398, 2001.
- [88] A. C. Edrington, A. M. Urbas, P. DeRege, C. X. Chen, T. M. Swager, N. Hadjichristidis, M. Xenidou, L. J. Fetters, J. D. Joannopoulos, Y. Fink, and E. L. Thomas, "Polymer-based photonic crystals," *Adv. Mater.*, vol. 13, pp. 421–425, 2001.
- [89] S. A. Jenekhe and X. L. Chen, "Self-assembly of ordered microporous materials from rod-coil block copolymers," *Science*, vol. 283, pp. 372–375, 1999.
- [90] Y. N. Xia, B. Gates, and Z. Y. Li, "Self-assembly approaches to three-dimensional photonic crystals," *Adv. Mater.*, vol. 13, pp. 409–413, 2001.
- [91] M. N. Shkunov, Z. V. Vardeny, M. C. DeLong, R. C. Polson, A. A. Zakhidov, and R. H. Baughman, "Tunable, gap-state lasing in switchable directions for opal photonic crystals," *Adv. Funct. Mater.*, vol. 12, pp. 21–26, 2002.
- [92] W. M. Lee, S. A. Pruzinsky, and P. V. Braun, "Multi-photon polymerization of waveguide structures within three-dimensional photonic crystals," *Adv. Mater.*, vol. 14, pp. 271–, 2002.
- [93] H. Miguez, S. M. Yang, N. Tetreault, and G. A. Ozin, "Oriented free-standing three-dimensional silicon inverted colloidal photonic crystal microribers," *Adv. Mater.*, vol. 14, pp. 1805–1808, 2002.
- [94] E. W. Seelig, B. Tang, A. Yamilov, H. Cao, and R. P. H. Chang, "Self-assembled 3-D photonic crystals from ZnO colloidal spheres," *Mater. Chem. Phys.*, vol. 80, pp. 257–263, 2003.
- [95] B. T. Holland, C. F. Blanford, and A. Stein, "Synthesis of macroporous minerals with highly ordered three-dimensional arrays of spheroidal voids," *Science*, vol. 281, pp. 538–540, 1998.
- [96] Y. D. Yin and Y. N. Xia, "Self-assembly of spherical colloids into helical chains with well-controlled handedness," *J. Amer. Chem. Soc.*, vol. 125, pp. 2048–2049, 2003.
- [97] P. D. Yang, A. H. Rizvi, B. Messer, B. F. Chmelka, G. M. Whitesides, and G. D. Stucky, "Patterning porous oxides within microchannel networks," *Adv. Mater.*, vol. 13, pp. 427–431, 2001.
- [98] A. A. Zakhidov, R. H. Baughman, Z. Iqbal, C. X. Cui, I. Khayrullin, S. O. Dantas, I. Marti, and V. G. Ralchenko, "Carbon structures with three-dimensional periodicity at optical wavelengths," *Science*, vol. 282, pp. 897–901, 1998.
- [99] D. J. Norris and Y. A. Vlasov, "Chemical approaches to three-dimensional semiconductor photonic crystals," *Adv. Mater.*, vol. 13, pp. 371–376, 2001.
- [100] J. E. n. G. n. J. Wijnhoven and W. L. Vos, "Preparation of photonic crystals made of air spheres in titania," *Science*, vol. 281, pp. 802–804, 1998.
- [101] P. D. Yang, T. Deng, D. Y. Zhao, P. Y. Feng, D. Pine, B. F. Chmelka, G. M. Whitesides, and G. D. Stucky, "Hierarchically ordered oxides," *Science*, vol. 282, pp. 2244–2246, 1998.
- [102] T. Thurn-Albrecht, J. DeRouchey, T. P. Russell, and H. M. Jaeger, "Overcoming interfacial interactions with electric fields," *Macromolecules*, vol. 33, pp. 3250–3253, 2000.
- [103] H. Miguez, S. M. Yang, and G. A. Ozin, "Optical properties of colloidal photonic crystals confined in rectangular microchannels," *Langmuir*, vol. 19, pp. 3479–3485, 2003.
- [104] X. L. Xu, S. A. Majetich, and S. A. Asher, "Mesoscopic monodisperse ferromagnetic colloids enable magnetically controlled photonic crystals," *J. Amer. Chem. Soc.*, vol. 124, pp. 13 864–13 868, 2002.



Babak Amir Parviz (S'94–M'01) received the B.S. degree in electrical engineering from the Sharif University of Technology, Tehran, Iran, in 1995, and the M.S. degree in electrical engineering, the M.S. degree in physics, and the Ph.D. degree in electrical engineering from the University of Michigan, Ann Arbor, in 1997 and 2001, respectively.

From 2000 to 2001, he was with Nanovation Technologies, Inc. as a Device Designer and Product Manager for MEMS-based integrated optical switches. Since 2001, he has been with

the Department of Chemistry and Chemical Biology, Harvard University, Cambridge, MA, as a Postdoctoral Research Fellow. His areas of interest are nano- and microfabrication, organic electronics, and MEMS.

Dr. Parviz received the Bronze Medal from the 22nd International Physics Olympiad, the First Place Kharazmi Award, and the Distinguished Achievement Award from the Electrical Engineering Department, University of Michigan.



Declan Ryan received the B.Sc. degree in chemistry from the University of Limerick, Ireland, in 1998 and the Ph.D. degree in chemistry from University College Dublin, Ireland, in 2001.

From 1998 to 1999, he was a Research Scientist for Ntera (a company focused on the application of nanostructured films in the areas of solar cells, displays, and sensors). Currently, he is an NIH Postdoctoral Fellow with the Department of Chemistry and Chemical Biology, Harvard University, Cambridge, MA. His research interests include colloidal and molecular self-assembly with specific focus on the use of self-assembled monolayers as tools for understanding cellular behavior.



George M. Whitesides was born in Louisville, KY, on August 3, 1939. He received the A.B. degree from Harvard University, Cambridge, MA, in 1960 and the Ph.D. degree from the California Institute of Technology, Pasadena, in 1964.

He was a member of the faculty of the Massachusetts Institute of Technology, Cambridge, from 1963 to 1982. He joined the Department of Chemistry, Harvard University, in 1982, and was Department Chairman from 1986 to 1989. He is currently the Mallinckrodt Professor of Chemistry at Harvard University. He is a member of the editorial board of the *Journal of Applied Biochemistry and Biotechnology*, *Bioorganic and Medicinal Chemistry Letters*, *Chemistry of Materials*, *Angewandte Chemie*, *Chemistry & Biology*, *Langmuir*, *Nanotechnology*, *Colloids and Surfaces B: Biointerfaces*, *Sensors and Actuators*, and *Electrophoresis*. His current areas of research include microtechnology and nanotechnology, self-assembly, physical organic chemistry, materials science, biophysics, complexity, surface science, microfluidics, and cell-surface biochemistry.

Dr. Whitesides received the American Chemical Society (ACS) Award of Pure Chemistry in 1976, the Arthur C. Cope Scholar Award (ACS) in 1989, the Arthur C. Cope Award (ACS) in 1995, the James Flack Norris Award in Physical Organic Chemistry (NE Section, ACS) in 1994, the Defense Advanced Research Projects Agency Award for Significant Technical Achievement in 1996, the National Medal of Science in 1998, the Von Hippel Award (Materials Research Society) in 2000, and the Kyoto Prize in 2003. He is a member of the National Academy of Science, the American Academy of Arts and Sciences, the American Philosophical Society, the Royal Netherlands Academy of Arts and Sciences, the New York Academy of Sciences, the World Technology Network, a Fellow of the American Association for the Advancement of Science, a Foreign Fellow of the Indian National Science Academy, and an Honorary Fellow of the Chemical Research Society of India.