The art of Building Small

BY GEORGE M. WHITESIDES
AND J. CHRISTOPHER LOVE

RESEARCHERS ARE DISCOVERING CHEAP,

EFFICIENT WAYS TO MAKE STRUCTURES

ONLY A FEW BILLIONTHS OF A METER ACROSS

INTRICATE DIFFRACTION PATTERNS are created by nanoscale-width rings (too small to see) on the surface of one-centimeter-wide hemispheres made of clear polymer. Kateri E. Paul, a graduate student in George M. Whitesides's group at Harvard University, fashioned the rings in a thin layer of gold on the hemispheres using a nanofabrication technique called soft lithography.

"Make it small!" is a technological edict that has changed the world. The development of microelectronics—first the transistor and then the aggregation of transistors into microprocessors, memory chips and controllers—has brought forth a cornucopia of machines that manipulate information by streaming electrons through silicon. Microelectronics rests on techniques that routinely fabricate structures almost as small as 100 nanometers across (that is, 100 billionths of a meter). This size is tiny by the standards of everyday experience—about one thousandth the width of a human hair—but it is large on the scale of atoms and molecules. The diameter of a 100-nanometer-wide wire would span about 500 atoms of silicon.

The idea of making "nanostructures" that comprise just one or a few atoms has great appeal, both as a scientific challenge and for practical reasons. A structure the size of an atom represents a fundamental limit: to make anything smaller would require manipulating atomic nuclei—essentially, transmuting one chemical element into another. In recent years, scientists have learned various techniques for building nanostructures, but they have only just begun to investigate their properties and potential applications. The age of nanofabrication is here, and the age of nanoscience has dawned, but the age of nanotechnology—finding practical uses for nanostructures—has not really started yet.

The Conventional Approach

RESEARCHERS may well develop nanostructures as electronic components, but the most important applications could be quite different: for example, biologists might use nanometer-scale particles as minuscule sensors to investigate cells. Because scientists do not know what kinds of nanostructures they will ultimately want to build, they have not yet determined the best ways to construct them. Photolithography, the technology used to manufacture computer chips and virtually all other microelectronic systems, can be refined to make structures smaller than 100 nanometers, but doing so is very difficult, expensive and inconvenient. In a search to find better alternatives, nanofabrication researchers have adopted the philosophy "Let a thousand flowers bloom."

First, consider the advantages and disadvantages of photolithography. Manufacturers use this phenomenally productive technology to churn out three billion transistors *per second* in the U.S. alone. Photolithography is basically an extension of photography. One first makes the equivalent of a photographic negative containing the pattern required for some part of a microchip's circuitry. This negative, which is called the mask or master, is then used to copy the pattern into the metals and semiconductors of a microchip. As is the case with photography, the negative may be hard to make, but creating multiple copies is easy, because the mask can be used many times. The process thus separates into two stages: the preparation of the mask (a one-time event, which can be slow and expensive) and the use of the mask to manufacture replicas (which must be rapid and inexpensive).

To make a mask for a part of a computer chip, a manufacturer first designs the circuitry pattern on a conveniently large scale and converts it into a pattern of opaque metallic film (usually chromium) on a transparent plate (usually glass or silica). Photolithography then reduces the size of the pattern in a process analogous to that used in a photographic darkroom [*see illustration on opposite page*]. A beam of light (typically ultraviolet light from a mercury arc lamp) shines through the chromium mask, then passes through a lens that focuses the image onto a photosensitive coating of organic polymer (called the photoresist) on the surface of a silicon wafer. The parts of the photoresist struck by the light can be selectively removed, exposing parts of the silicon wafer in a way that replicates the original pattern.

Why not use photolithography to make nanostructures? The technology faces two limitations. The first is that the shortest wavelength of ultraviolet light currently used in production processes is about 250 nanometers. Trying to make structures much smaller than half of that spacing is like trying to read print that is

Overview/*Nanofabrication*

- The development of nanotechnology will depend on the ability of researchers to efficiently manufacture structures smaller than 100 nanometers (100 billionths of a meter) across.
- Photolithography, the technology now used to fabricate circuits on microchips, can be modified to produce nanometer-scale structures, but the modifications would be technically difficult and hugely expensive.
- Nanofabrication methods can be divided into two categories: top-down methods, which carve out or add aggregates of molecules to a surface, and bottom-up methods, which assemble atoms or molecules into nanostructures.
- Two examples of promising top-down methods are soft lithography and dip-pen lithography. Researchers are using bottom-up methods to produce quantum dots that can serve as biological dyes.
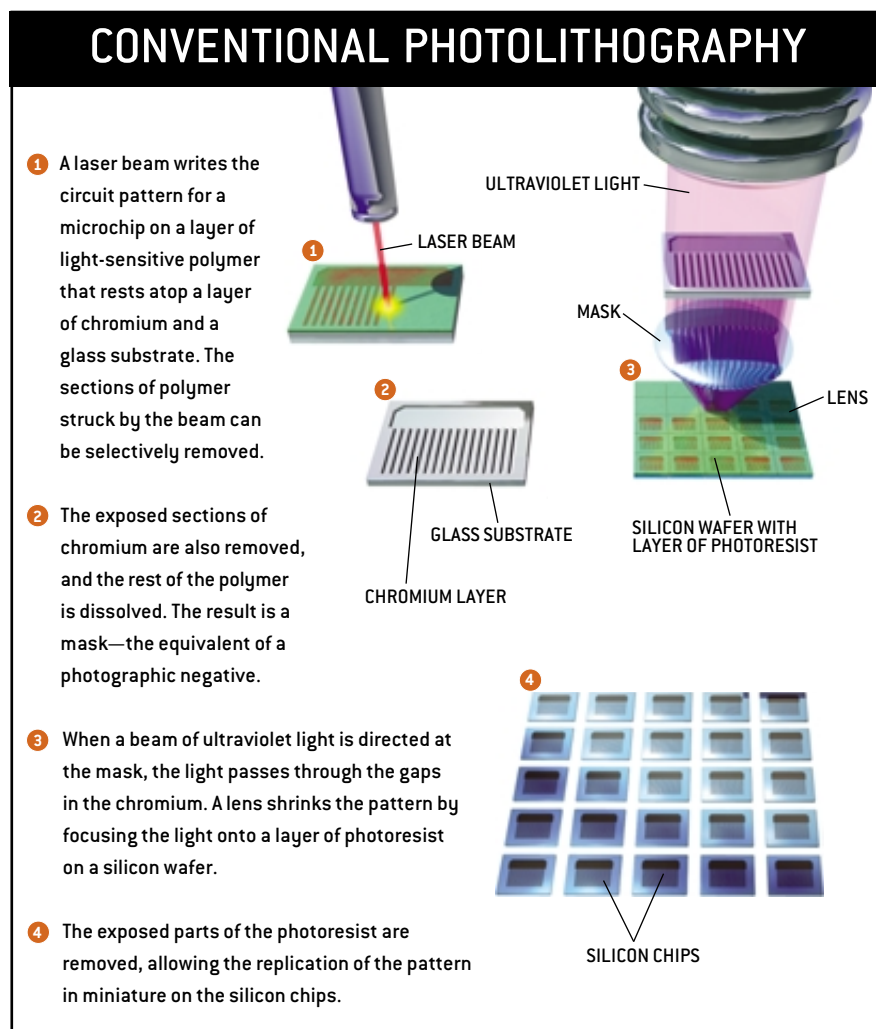
too tiny: diffraction causes the features to blur and meld together. Various technical improvements have made it possible to push the limits of photolithography. The smallest structures created in mass production are somewhat larger than 100 nanometers, and complex microelectronic structures have been made with features that are only 70 nanometers across. But these structures are still not small enough to explore some of the most interesting aspects of nanoscience.

The second limitation follows from the first: because it is technically difficult to make such small structures using light, it is also very expensive to do so. The photolithographic tools that will be used to make chips with features well below 100 nanometers will each cost tens to hundreds of millions of dollars. This expense may or may not be acceptable to manufacturers, but it is prohibitive for the biologists, materials scientists, chemists and physicists who wish to explore nanoscience using structures of their own design.

Future Nanochips

THE ELECTRONICS industry is deeply interested in developing new methods for nanofabrication so that it can continue its long-term trend of building ever smaller, faster and less expensive devices. It would be a natural evolution of microelectronics to become nanoelectronics. But because conventional photolithography becomes more difficult as the dimensions of the structures become smaller, manufacturers are exploring alternative technologies for making future nanochips.

One leading contender is electron-beam lithography. In this method, the circuitry pattern is written on a thin polymer film with a beam of electrons. An electron beam does not diffract at atomic scales, so it does not cause blurring of the edges of features. Researchers have used the technique to write lines with widths of only a few nanometers in a layer of photoresist on a silicon substrate. The electron-beam instruments currently available, however, are very expensive and impractical for large-scale manufacturing. Because the beam of electrons is needed to fabricate each structure, the process is similar to the copying of a manuscript by hand, one line at a time.

If electrons are not the answer, what is? Another contender is lithography using x-rays with wavelengths between 0.1 and 10 nanometers or extreme ultraviolet light with wavelengths between 10 and 70 nanometers. Because these forms of radiation have much shorter wavelengths than the ultraviolet light currently used in photolithography, they minimize the blurring caused by diffraction. These technologies face their own set of problems, however: conventional lenses are not transparent to extreme ultraviolet light and do not focus x-rays. Furthermore, the energetic radiation rapidly damages many of the materials used in masks and lenses. But the microelectronics industry clearly would prefer to make advanced chips using extensions of familiar technology, so these methods are being actively developed. Some of the techniques (for example, advanced ultraviolet lithography for chip production) will probably become commercial realities. They will not, though, make inexpensive nanostructures and thus will do nothing to open nanotechnology to a broader group of scientists and engineers.

The need for simpler and less expensive methods of fabricating nanostructures has stimulated the search for un-

CONVENTIONAL PHOTOLITHOGRAPHY

1 A laser beam writes the circuit pattern for a microchip on a layer of light-sensitive polymer that rests atop a layer of chromium and a glass substrate. The sections of polymer struck by the beam can be selectively removed.

2 The exposed sections of chromium are also removed, and the rest of the polymer is dissolved. The result is a mask—the equivalent of a photographic negative.

3 When a beam of ultraviolet light is directed at the mask, the light passes through the gaps in the chromium. A lens shrinks the pattern by focusing the light onto a layer of photoresist on a silicon wafer.

4 The exposed parts of the photoresist are removed, allowing the replication of the pattern in miniature on the silicon chips.

LASER BEAM
ULTRAVIOLET LIGHT
MASK
LENS
SILICON WAFER WITH LAYER OF PHOTORESIST
GLASS SUBSTRATE
CHROMIUM LAYER
SILICON CHIPS

THE AUTHORS

GEORGE M. WHITESIDES and J. CHRISTOPHER LOVE work together on unconventional methods of nanofabrication in the department of chemistry at Harvard University. Whitesides, a professor of chemistry, received his Ph.D. from the California Institute of Technology in 1964 and joined the Harvard faculty in 1982. Love is a graduate student and a member of Whitesides's research group. He received his bachelor's degree in chemistry from the University of Virginia in 1999 and his master's degree from Harvard in 2001.

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SOFT LITHOGRAPHY

Printing, molding and other mechanical processes carried out using an elastic stamp can produce patterns with nanoscale features.

Such techniques can fabricate devices that might be used in optical communications or biochemical research.

MAKING AN ELASTIC STAMP

1 A liquid precursor to polydimethylsiloxane (PDMS) is poured over a bas-relief master produced by photolithography or electron-beam lithography.

2 The liquid is cured into a rubbery solid that matches the original pattern.

3 The PDMS stamp is peeled off the master.

LIQUID PRECURSOR TO PDMS

PDMS STAMP

MASTER

PHOTORESIST
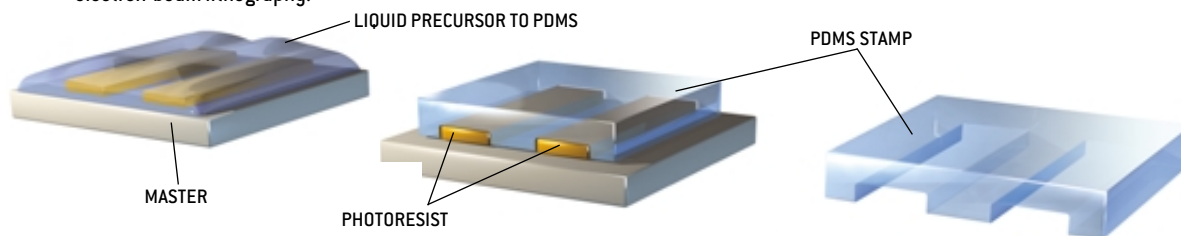
MICROCONTACT PRINTING

1 The PDMS stamp is inked with a solution consisting of organic molecules called thiols and then pressed against a thin film of gold on a silicon plate.

2 The thiols form a self-assembled monolayer on the gold surface that reproduces the stamp's pattern; features in the pattern are as small as 50 nanometers.

GOLD SURFACE

THIOL INK

SELF-ASSEMBLED MONOLAYER

MICROMOLDING IN CAPILLARIES
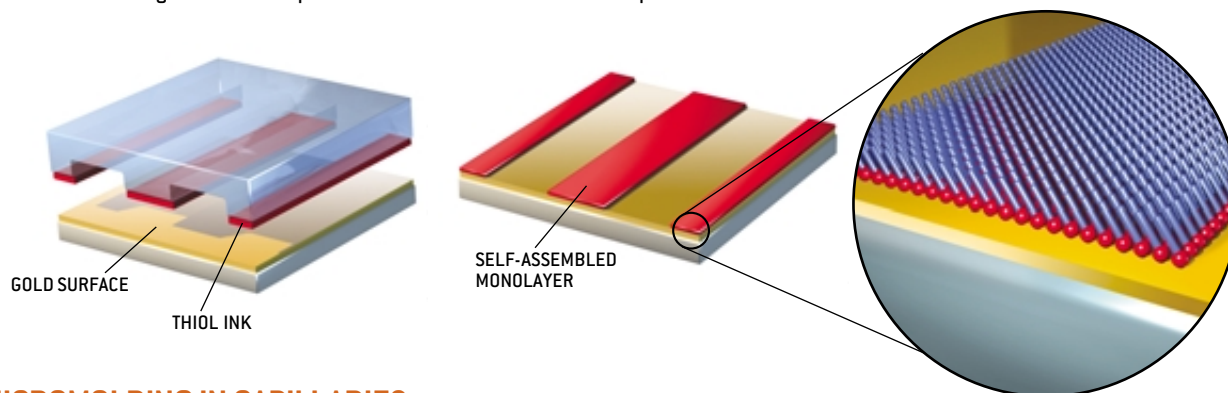
SOLIDIFIED POLYMER

LIQUID POLYMER

1 The PDMS stamp is placed on a hard surface, and a liquid polymer flows into the recesses between the surface and the stamp.

2 The polymer solidifies into the desired pattern, which may contain features smaller than 10 nanometers.
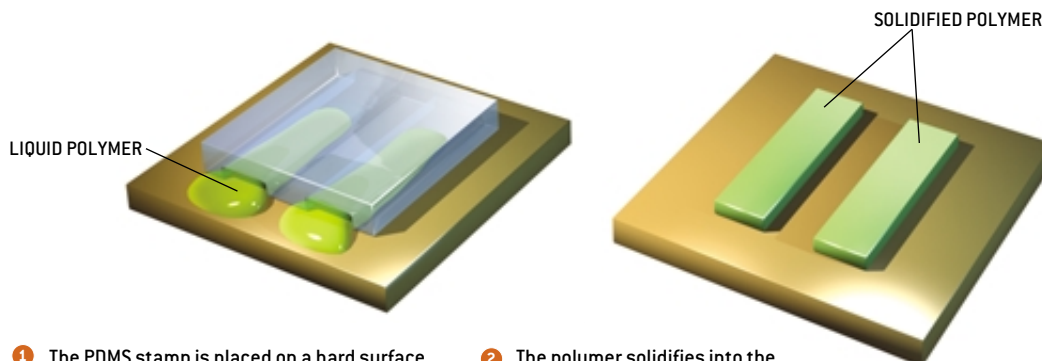
conventional approaches that have not been explored by the electronics industry. We first became interested in the topic in the 1990s when we were engaged in making the simple structures required in microfluidic systems—chips with channels and chambers for holding liquids. This lab-on-a-chip has myriad potential uses in biochemistry, ranging from drug screening to genetic analysis. The channels in microfluidic chips are enormous by the standards of microelectronics: 50 microns (or 50,000 nanometers) wide, rather than 100 nanometers. But the techniques for producing those channels are quite versatile. Microfluidic chips can be made quickly and inexpensively, and many are composed of organic polymers and gels—materials not found in the world of electronics. We discovered that

matches the original pattern with astonishing fidelity: the stamp reproduces features from the master as small as a few nanometers. Although the creation of a finely detailed bas-relief master is expensive because it requires electron-beam lithography or other advanced techniques, copying the pattern on PDMS stamps is cheap and easy. And once a stamp is in hand, it can be used in various inexpensive ways to make nanostructures.

The first method—originally developed by Amit Kumar, a postdoctoral student in our group at Harvard University—is called microcontact printing. The PDMS stamp is "inked" with a reagent solution consisting of organic molecules called thiols [*see middle illustration on opposite page*]. The stamp is then brought into contact with an appropriate sheet of

are in the field of nanofluidics, an extension of microfluidics that would involve producing chips for biochemical research with channels only a few nanometers wide. At that scale, fluid dynamics may allow new ways to separate materials such as fragments of DNA.

These methods require no special equipment and in fact can be carried out by hand in an ordinary laboratory. Conventional photolithography must take place in a clean-room facility devoid of dust and dirt; if a piece of dust lands on the mask, it will create an unwanted spot on the pattern. As a result, the device being fabricated (and sometimes neighboring devices) may fail. Soft lithography is generally more forgiving because the PDMS stamp is elastic. If a piece of dust gets trapped between the stamp and the sur-

These methods require no special equipment and in fact can be carried out by hand in an ordinary lab.

we could use similar techniques to create nanostructures.

The methods represented, in a sense, a step backward in technology. Instead of using the tools of physics—light and electrons—we employed mechanical processes that are familiar in everyday life: printing, stamping, molding and embossing. The techniques are called soft lithography because the tool they have in common is a block of polydimethylsiloxane (PDMS)—the rubbery polymer used to caulk the leaks around bathtubs. (Physicists often refer to such organic chemicals as "soft matter.")

To carry out reproduction using soft lithography, one first makes a mold or a stamp. The most prevalent procedure is to use photolithography or electron-beam lithography to produce a pattern in a layer of photoresist on the surface of a silicon wafer. This process generates a bas-relief master in which islands of photoresist stand out from the silicon [*see top illustration on opposite page*]. Then a chemical precursor to PDMS—a free-flowing liquid—is poured over the bas-relief master and cured into the rubbery solid. The result is a PDMS stamp that

"paper"—a thin film of gold on a glass, silicon or polymer plate. The thiols react with the gold surface, forming a highly ordered film (called a self-assembled monolayer, or SAM) that replicates the stamp's pattern. Because the thiol ink spreads a bit after it contacts the surface, the resolution of the monolayer cannot be quite as high as that of the PDMS stamp. But when used correctly, microcontact printing can produce patterns with features as small as 50 nanometers.
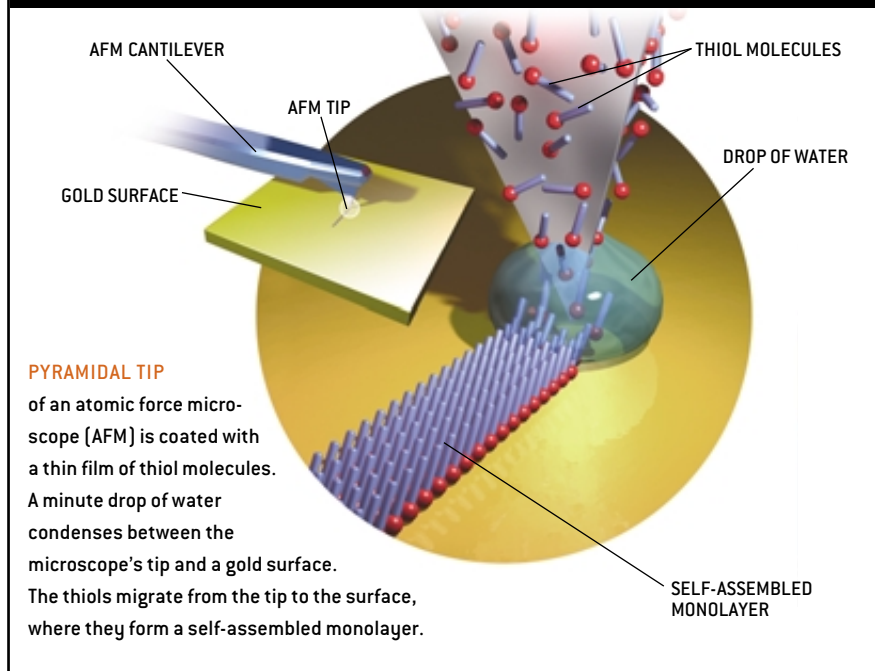
Another method of soft lithography, called micromolding in capillaries, involves using the PDMS stamp to mold patterns. The stamp is placed on a hard surface, and a liquid polymer flows by capillary action into the recesses between the surface and the stamp [*see bottom illustration on opposite page*]. The polymer then solidifies into the desired pattern. This technique can replicate structures smaller than 10 nanometers. It is particularly well suited for producing subwavelength optical devices, waveguides and optical polarizers, all of which could be used in optical fiber networks and eventually perhaps in optical computers. Other possible applications

face, the stamp will compress over the top of the particle but maintain contact with the rest of the surface. Thus, the pattern will be reproduced correctly except for where the contaminant is trapped.

Moreover, soft lithography can produce nanostructures in a wide range of materials, including the complex organic molecules needed for biological studies. And the technique can print or mold patterns on curved as well as planar surfaces. But the technology is not ideal for making the structures required for complex nanoelectronics. Currently all integrated circuits consist of stacked layers of different materials. Deformations and distortions of the soft PDMS stamp can produce small errors in the replicated pattern and a misalignment of the pattern with any underlying patterns previously fabricated. Even the tiniest distortions or misalignments can destroy a multilayered nanoelectronic device. Therefore, soft lithography is not well suited for fabricating structures with multiple layers that must stack precisely on top of one another.

Researchers have found ways, however, to correct this shortcoming—at

DIP-PEN LITHOGRAPHY

AFM CANTILEVER

AFM TIP

THIOL MOLECULES

GOLD SURFACE

DROP OF WATER

PYRAMIDAL TIP

of an atomic force micro-
scope (AFM) is coated with
a thin film of thiol molecules.
A minute drop of water
condenses between the
microscope's tip and a gold surface.
The thiols migrate from the tip to the surface,
where they form a self-assembled monolayer.

SELF-ASSEMBLED
MONOLAYER

least in part—by employing a rigid stamp instead of an elastic one. In a technique called step-and-flash imprint lithography, developed by C. Grant Willson of the University of Texas, photolithography is used to etch a pattern into a quartz plate, yielding a rigid bas-relief master. Willson eliminated the step of making a PDMS stamp from the master; instead the master itself is pressed against a thin film of liquid polymer, which fills the master's recesses. Then the master is exposed to ultraviolet light, which solidifies the polymer to create the desired replica. A related technique called nanoimprint lithography, developed by Stephen Y. Chou of Princeton University, also employs a rigid master but uses a film of polymer that has been heated to a temperature near its melting point to facilitate the embossing process. Both methods can produce two-dimensional structures with good fidelity, but it remains to be seen whether the techniques are suitable for manufacturing electronic devices.

Pushing Atoms Around

THE CURRENT REVOLUTION in nanoscience started in 1981 with the invention of the scanning tunneling microscope (STM), for which Heinrich Rohrer and Gerd K. Binnig of the IBM Zurich Research Laboratory received the Nobel Prize in Physics in 1986. This remarkable device detects small currents that pass between the microscope's tip and the sample being observed, allowing researchers to "see" substances at the scale of individual atoms. The success of the STM led to the development of other scanning probe devices, including the atomic force microscope (AFM). The operating principle of the AFM is similar to that of an old-fashioned phonograph. A tiny probe—a fiber or a pyramid-shaped tip that is typically between two and 30 nanometers wide—is brought into direct contact with the sample. The probe is attached to the end of a cantilever, which bends as the tip moves across the sample's surface. The deflection is measured by reflecting a beam of laser light off the top of the cantilever. The AFM can detect variations in vertical surface topography that are smaller than the dimensions of the probe.

But scanning probe devices can do more than simply allow scientists to observe the atomic world—they can also be used to create nanostructures. The tip on the AFM can be used to physically move nanoparticles around on surfaces and to arrange them in patterns. It can also be used to make scratches in a surface (or

more commonly, in monolayer films of atoms or molecules that coat the surface). Similarly, if researchers increase the currents flowing from the tip of the STM, the microscope becomes a very small source for an electron beam, which can be used to write nanometer-scale patterns. The STM tip can also push individual atoms around on a surface to build rings and wires that are only one atom wide.

An intriguing new scanning probe fabrication method is called dip-pen lithography. Developed by Chad A. Mirkin of Northwestern University, this technique works much like a goose-feather pen [*see illustration at left*]. The tip of the AFM is coated with a thin film of thiol molecules that are insoluble in water but react with a gold surface (the same chemistry used in microcontact printing). When the device is placed in an atmosphere containing a high concentration of water vapor, a minute drop of water condenses between the gold surface and the microscope's tip. Surface tension pulls the tip to a fixed distance from the gold, and this distance does not change as the tip moves across the surface. The drop of water acts as a bridge over which the thiol molecules migrate from the tip to the gold surface, where they are fixed. Researchers have used this procedure to write lines a few nanometers across.

Although dip-pen lithography is relatively slow, it can use many different types of molecules as "inks" and thus brings great chemical flexibility to nanometer-scale writing. Researchers have not yet determined the best applications for the technique, but one idea is to use the dip-pen method for precise modifications of circuit designs. Mirkin has recently demonstrated that a variant of the ink used in dip-pen lithography can write directly on silicon.

An interesting cousin to these techniques involves another kind of nanostructure, called a break junction. If you break a thin, ductile metal wire into two parts by pulling sharply, the process seems abrupt to a human observer, but it actually follows a complex sequence. When the force used in breaking the wire is first applied, the metal begins to yield and flow, and the diameter of the wire

decreases. As the two ends move apart, the wire gets thinner and thinner until, in the instant just before breaking, it is a single atom in diameter at its narrowest point. This process of thinning a wire to a break junction can be detected easily by measuring the current that flows through the wire. When the wire is slender enough, current can flow only in discrete quantities (that is, current flow is quantized).

The break junction is analogous to two STM tips facing each other, and similar physical rules govern the current that flows through it. Mark A. Reed of Yale University has pioneered a particularly inventive use of the break junction. He built a device that enabled a thin junction to be broken under carefully controlled conditions and then allowed the broken tips to be brought back together or to be held apart at any distance with an accuracy of a few thousandths of a nanometer. By adjusting the distance between the tips in the presence of an organic molecule that bridged them, Reed was able to measure a current flowing across the organic bridge. This experiment was an important step in the development of technolo-

gies for using single organic molecules as electronic devices such as diodes and transistors [see "Computing with Molecules," by Mark A. Reed and James M. Tour; Scientific American, June 2000].

Top-Down and Bottom-Up

ALL THE FORMS of lithography we have discussed so far are called top-down methods—that is, they begin with a pattern generated on a larger scale and reduce its lateral dimensions (often by a factor of 10) before carving out nanostructures. This strategy is required in fabricating electronic devices such as microchips, whose functions depend more on their patterns than on their dimensions. But no top-down method is ideal; none can conveniently, cheaply and quickly make nanostructures of any material. So researchers have shown growing interest in bottom-up methods, which start with atoms or molecules and build *up* to nanostructures. These methods can easily make the smallest nanostructures—with dimensions between two and 10 nanometers—and do so inexpensively. But these structures are usu-

ally generated as simple particles in suspension or on surfaces, rather than as designed, interconnected patterns.

Two of the most prominent bottom-up methods are those used to make nanotubes and quantum dots. Scientists have made long, cylindrical tubes of carbon by a catalytic growth process that employs a nanometer-scale drop of molten metal (usually iron) as a catalyst [see "Nanotubes for Electronics," by Philip G. Collins and Phaedon Avouris; Scientific American, December 2000]. The most active area of research in quantum dots originated in the laboratory of Louis E. Brus (then at Bell Laboratories) and has been developed by A. Paul Alivisatos of the University of California at Berkeley, Moungi G. Bawendi of the Massachusetts Institute of Technology, and others. Quantum dots are crystals containing only a few hundred atoms. Because the electrons in a quantum dot are confined to widely separated energy levels, the dot emits only one wavelength of light when it is excited. This property makes the quantum dot useful as a biological marker [see

Nanofabrication: Comparing the Methods

Researchers are developing an array of techniques for building structures smaller than 100 nanometers. Here is a summary of the advantages and disadvantages of four methods.

Photolithography
Advantages: The electronics industry is already familiar with this technology because it is currently used to fabricate microchips. Manufacturers can modify the technique to produce nanometer-scale structures by employing electron beams, x-rays or extreme ultraviolet light.
Disadvantages: The necessary modifications will be expensive and technically difficult. Using electron beams to fashion structures is costly and slow. X-rays and extreme ultraviolet light can damage the equipment used in the process.

Soft Lithography
Advantages: This method allows researchers to inexpensively reproduce patterns created by electron-beam lithography or other related techniques. Soft lithography requires no special equipment and can be carried out by hand in an ordinary laboratory.
Disadvantages: The technique is not ideal for manufacturing the multilayered structures of electronic devices. Researchers are trying to overcome this drawback, but it remains to be seen whether these efforts will be successful.

Scanning Probe Methods
Advantages: The scanning tunneling microscope and the atomic force microscope can be used to move individual nanoparticles and arrange them in patterns. The instruments can build rings and wires that are only one atom wide.
Disadvantages: The methods are too slow for mass production. Applications of the microscopes will probably be limited to the fabrication of specialized devices.

Bottom-Up Methods
Advantages: By setting up carefully controlled chemical reactions, researchers can cheaply and easily assemble atoms and molecules into the smallest nanostructures, with dimensions between two and 10 nanometers.
**Disadvantages:** Because these methods cannot produce designed, interconnected patterns, they are not well suited for building electronic devices such as microchips.

QUANTUM DOT ASSEMBLY

Crystals called quantum dots contain only a few hundred atoms and emit different wavelengths of light, depending on their size. They may become useful as biological markers of cellular activity.
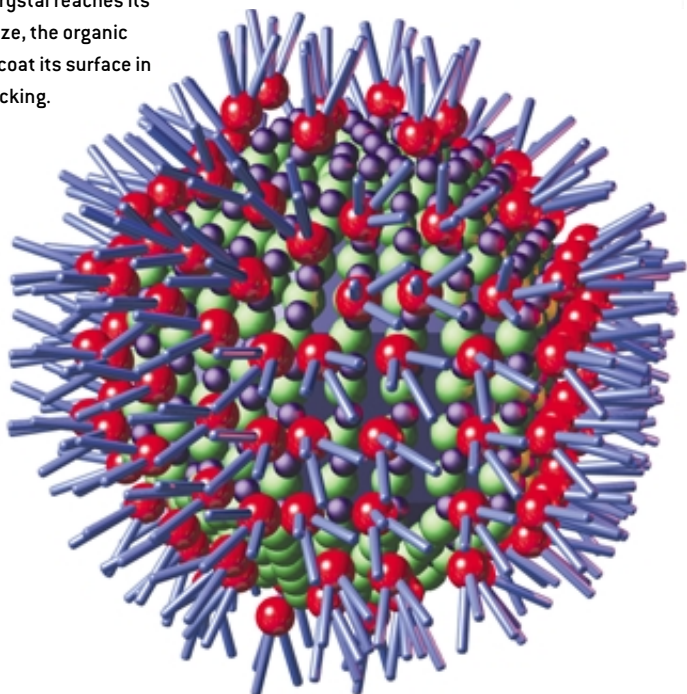
1. A chemical reaction brings together cadmium ions (*purple*), selenium ions (*green*) and organic molecules (*red spheres with blue tails*).
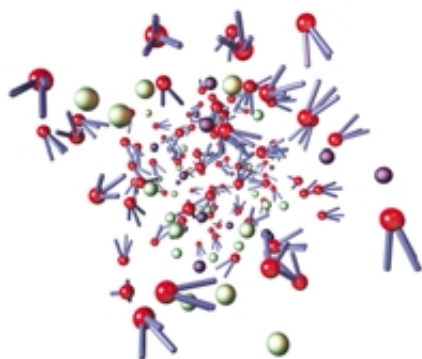
2. The organic molecules act as surfactants, binding to the surface of the cadmium selenide crystal as it grows.
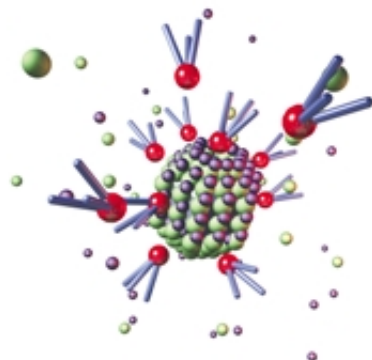
3. When the crystal reaches its optimum size, the organic molecules coat its surface in a stable packing.

One procedure used to make quantum dots involves a chemical reaction between a metal ion (for example, cadmium) and a molecule that is able to donate a selenium ion. This reaction generates crystals of cadmium selenide. The trick is to prevent the small crystals from sticking together as they grow to the desired size. To insulate the growing particles from one another, researchers carry out the reaction in the presence of organic molecules that act as surfactants, coating the surface of each cadmium selenide particle as it grows. The organic molecules stop the crystals from clumping together and regulate their rate of growth. The geometry of the particles can be controlled to some extent by mixing different ratios of the organic molecules. The reaction can generate particles with a variety of shapes, including spheres, rods and tetrapods (four-armed particles similar to toy jacks).

It is important to synthesize the quantum dots with uniform size and composition, because the size of the dot determines its electronic, magnetic and optical properties. Researchers can select the size of the particles by varying the length of time for the reaction. The organic coating also helps to set the size of the particles. When the nanoparticle is small (on the scale of molecules), the organic coating is loose and allows further growth; as the particle enlarges, the organic molecules become crowded. There is an optimum size for the particles that allows the most stable packing of the organic molecules and thus provides the greatest stabilization for the surfaces of the crystals.

These cadmium selenide nanoparticles promise some of the first commercial products of nanoscience: Quantum Dot Corporation has been developing the crystals for use as biological labels. Researchers can tag proteins and nucleic acids with quantum dots; when the sample is illuminated with ultraviolet light, the crystals will fluoresce at a specific wavelength and thus show the locations of the attached proteins. Many organic molecules also fluoresce, but quantum dots have several advantages that make them better markers. First, the color of

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a quantum dot's fluorescence can be tailored by changing the dot's size: the larger the particle, the more the emitted light is shifted toward the red end of the spectrum. Second, if all the dots are the same size, their fluorescence spectrum is narrow—that is, they emit a very pure color. This property is important because it allows particles of different sizes to be used as distinguishable labels. Third, the fluorescence of quantum dots does not fade on exposure to ultraviolet light, as does that of organic molecules. When used as dyes in biological research, the dots can be observed for conveniently long periods.

Scientists are also investigating the possibility of making structures from colloids—nanoparticles in suspension. Christopher B. Murray and a team at the IBM Thomas J. Watson Research Center are exploring the use of such colloids to create a medium for ultrahigh-density data storage. The IBM team's colloids contain magnetic nanoparticles as small as

mammalian cells are larger. Cells are, however, filled with much smaller structures, many of which are astonishingly sophisticated. The ribosome, for example, carries out one of the most important cellular functions: the synthesis of proteins from amino acids, using messenger RNA as the template. The complexity of this molecular construction project far surpasses that of man-made techniques. Or consider the rotary motors of the bacterial flagella, which efficiently propel the one-celled organisms [see "The Once and Future Nanomachine," on page 78].

It is unclear if "nanomachines" taken from cells will be useful. They will probably have very limited application in electronics, but they may provide valuable tools for chemical synthesis and sensing devices. Recent work by Carlo D. Montemagno of Cornell University has shown that it is possible to engineer a primitive nanomachine with a biological engine. Montemagno extracted a rotary motor protein from a bacterial cell and

The development of nanotechnology will depend on the availability of nanostructures. The invention of the STM and AFM has provided new tools for viewing, characterizing and manipulating these structures; the issue now is how to build them to order and how to design them to have new and useful functions. The importance of electronics applications has tended to focus attention on nanodevices that might be incorporated into future integrated circuits. And for good technological reasons, the electronics industry has emphasized fabrication methods that are extensions of those currently used to make microchips. But the explosion of interest in nanoscience has created a demand for a broad range of fabrication methods, with an emphasis on low-cost, convenient techniques.

The new approaches to nanofabrication are unconventional only because they are not derived from the microtechnology developed for electronic devices.

Bottom-up methods start from atoms or molecules and build up to nanostructures.

three nanometers across, each composed of about 1,000 iron and platinum atoms. When the colloid is spread on a surface and the solvent allowed to evaporate, the nanoparticles crystallize in two- or three-dimensional arrays. Initial studies indicate that these arrays can potentially store trillions of bits of data per square inch, giving them a capacity 10 to 100 times greater than that of present memory devices.

The Future of Nanofabrication

THE INTEREST in nanostructures is so great that every plausible fabrication technique is being examined. Although physicists and chemists are now doing most of the work, biologists may also make important contributions. The cell (whether mammalian or bacterial) is relatively large on the scale of nanostructures: the typical bacterium is approximately 1,000 nanometers long, and

connected it to a metallic nanorod—a cylinder 750 nanometers long and 150 nanometers wide that had been fabricated by lithography. The rotary motor, which was only 11 nanometers tall, was powered by adenosine triphosphate (ATP), the source of chemical energy in cells. Montemagno showed that the motor could rotate the nanorod at eight revolutions per minute. At the very least, such research stimulates efforts to fabricate functional nanostructures by demonstrating that such structures can exist.

Chemists, physicists and biologists are rapidly accepting these techniques as the most appropriate ways to build various kinds of nanostructures for research. And the methods may even supplement the conventional approaches—photolithography, electron-beam lithography and related techniques—for applications in electronics as well. The microelectronics mold is now broken. Ideas for nanofabrication are coming from many directions in a wonderful free-for-all of discovery. SA

MORE TO EXPLORE

More information about nanofabrication can be found at the following Web sites:

International SEMATECH: **www.sematech.org/public/index.htm**

The Whitesides group at Harvard University: **gmwgroup.harvard.edu**

The Mirkin group at Northwestern University: **www.chem.northwestern.edu/~mkngrp/**

The Willson group at the University of Texas at Austin: **willson.cm.utexas.edu/Research/research.htm**

The Alivisatos group at the University of California at Berkeley: **www.cchem.berkeley.edu/~pagrp/**

The Bawendi group at M.I.T.: **web.mit.edu/chemistry/nanocluster/**

The Montemagno group at Cornell University: **falcon.aben.cornell.edu/**