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Introduction to nanotechnology - soft lithography

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1 Introduction

Today there is a nanotechnology gold-rush. Nearly every major funding agency for science and engineering has announced its own thrust into the field. Scores of researchers and institutions are scrambling for a piece of the action. The actual pioneer of current activities was Nobel laureate *Richard Feynman*. Back in December 1959 he gave visionary and now oft-quoted talk entitled "There's Plenty of Room at the Bottom".][1,2] His 7000 words were defining moment in nanotechnology, long before anything "nano" appeared on the horizon. He discussed what is possible in principle and anticipated a spectrum of scientific and technical fields that are now well established, among them electron-beam and ion-beam fabrication, molecular-beam epitaxy, nanoimprint lithography, projection electron microscopy, atom-by-atom manipulation, quantum electronics, spin electronics (also called spintronics) and microelectromechanical systems (MEMS). His talk has profoundly inspired many of leading scientists in the field of nanotechnology, that is why we can see Feynman as the father of current nanoactivities.

The definition of nanotechnology is slippery. Some of nanotechnology isn't nano, dealing instead with structures on the micron scale, 1000 times or more larger then a nanometer. Also, nanotechnology, in many cases, isn't technology. Rather it involves basic research on structures having at least one dimension of about one to several hundred nanometers. To add still more confusion, some nanotechnology has been around for a while: nano-size carbon black particles (a.k.a. high-tech soot) have gone into tires for 100 years as a reinforcing additive, long before "nano" ever created a stir. For that matter, a vaccine, which often consists of one or more proteins with nanoscale dimensions, might also qualify.

But there is a *there* there in both nanoscience and nanotechnology. The nanoworld is a weird borderland between the realm of individual atoms and molecules (where quantum mechanics rules) and the macroworld (where bulk properties of materials emerge from the collective behavior of trillions of atoms, whether that material is a steel beam or the cream filling in a chocolate bar). At the bottom end, in the region of one nanometer, nanoland bumps up against basic building blocks of matter. As such, it defines the smallest natural structures and sets a hard limit to shrinkage: you just can't built things any smaller.

2 Physical laws

We've only just begun to take the first step toward Feynman's grand vision of assembling complex machines and circuits atom by atom. What can be done now is extremely rudimentary. We're certainly nowhere near being able to commercially mass-produce nanosystems-integrated multicomponent nanodevices that have the complexity and range of functions readily provided by modern microchips. But there is a fundamental science issue here as well. It is becoming increasingly clear that we are only *beginning* to acquire the knowledge that will be at the heart of future nanotechnology. This new science concerns the properties and behavior of aggregates of atoms and molecules, at a scale not yet large enough to be considered macroscopic but far beyond what can be called microscopic. It is the science of the *mesoscale*, and until we understand it, practical devices will be difficult to realize.

Today's scientists and engineers readily fashion nanostructures on a scale of one to hundred nanometers - small indeed, but much bigger than simple molecules [2] . Matter at this scale is often awkward to explore. It contains too many atoms to be easily understood by straightforward application of quantum mechanics (although the fundamental laws still apply). Yet these systems are not so large as to be completely free of quantum effects; thus, they do not simply obey the classical physics governing macroworld. It is precisely in this intermediate domain, the mesoworld, that unforseen properties of collective systems emerge. Science has discovered some new universal rules of nanoworld, that have become laws of nanotechnology.

2.1 Quantization of electrical conductance

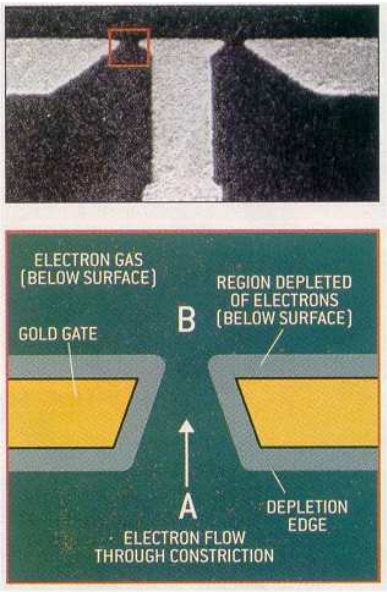

Figure 1: Experiment

In 1987 Bart J. van Wees and his collaborators at the Delft University of Technology and Philips Research Laboratories [both in the Netherlands] built a novel structure [*micrograph*] that revealed a basic law governing nanotech circuits [2,5]. They studied the resistance of ballistic point contacts in the two-dimensional (2DEG) electron gas of high-mobility GaAs-AlGaAl heterostructures. The point contacts re defined by electrostatic depletion of the 2DEG underneath a gate. Using electron-beam lithography, a metal gate [gold] is made on top of the heterostructure [figure 1], with an opening 250 nm wide. The point contacts are defined by the application of negative voltage to the gate. If two pieces of metal and semiconductor are put together, Fermi surface of the metal and chemical potential of semiconductor are aligned. Because both levels, in general, aren't at the same hight, the current carriers from semiconductor migrate into the metal, leaving behind an area, that doesn't conduct current.

This area - *depletion area*- depends on hight of Fermi surface in metal, which can be controlled through negative bias applied on it. That's the mechanism they used to change width of the constriction (Figure 1).

They measured the resistance of several point contacts as a function of gate voltage in zero magnetic field at 0.6 K. *Unexpected, plateaus were found in the resistance.*

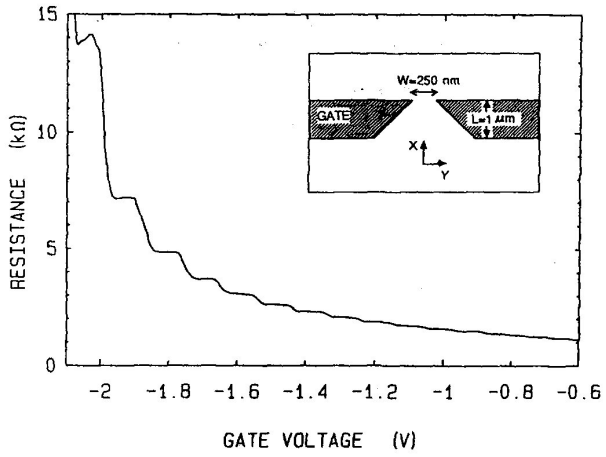

Figure 2: Point-contact resistance as a function of gate voltage at 0.6 K. Inset: Point-contact layout

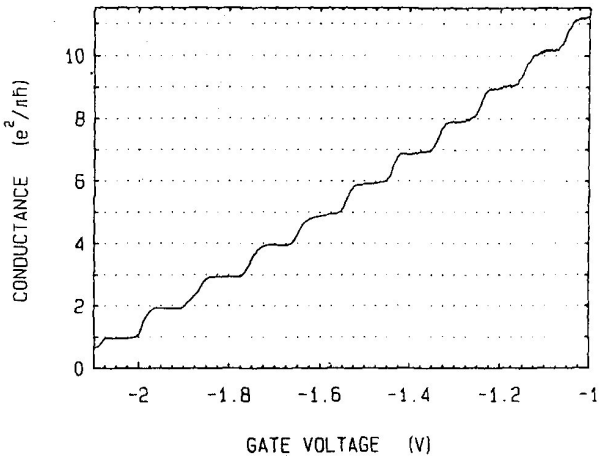

Figure 3: Point-contact conductance as a function of gate voltage, obtained from the data of Figure 2 after subtraction of the lead resistance. The conductance shows plateaus at multiples of $e^2/\pi\hbar$.

Plot on figure 3, calculated from the measured resistance subtraction of a lead resistance 400Ω, shows clear plateaus at integer multiples of $e^2/\pi\hbar$.

An explanation of observed quantization could be proposed based on assumption of quantization transverse momentum in the contact constriction. We can derive the conductivity from the definition of electrical current:

$$I = \frac{\Delta e}{\Delta t} = \Delta e \frac{v}{L}, \tag{1}$$

where L is the length of the constriction. Charge can be obtained through the density of energetic electron states in two-dimensional electron gas, the velocity can be connected with wave vector of electrons:

$$I = e(\frac{dg}{dE})eUW(\frac{\hbar}{2m})\langle|k_x|\rangle, \tag{2}$$

where W is the width of the constriction. Current is proportional to voltage and the coefficient is the conductivity of the constriction. The point-contact conductance G for ballistic transport is than given by:

$$G = e^2 N_0 W(\hbar/2m)\langle|k_x|\rangle \tag{3}$$

The brackets denote an average of longitudinal wave vector k_x over direction on the Fermi circle, $N_0 = m/\pi\hbar$ is the density of states in the two-dimensional electron gas. The Fermi-circle average is taken over discrete transverse wave vectors $k_y = \pm n\pi/W$ (n=1,2,...), so that we can write:

$$\langle|k_x|\rangle = \frac{1}{2\pi k_F}\int d^2k|k_x|\delta(k-k_F)\frac{2\pi}{W}\sum_{n=1}^{\infty}\delta(k_y - \frac{n\pi}{W}). \tag{4}$$

Carrying out the integration and substituting into Eq. 3, one obtains the result

$$G = \sum_{n=1}^{N_C} e^2/\pi\hbar \tag{5}$$

where the number of channels (or one-dimensional subbands) N_C is the largest integer smaller than $k_F W/\pi$. For $k_F W \gg 1$ this expression reduces to the classical formula

$$G = (e^2/\pi\hbar)k_F/\pi \tag{6}$$

Equation 5 tells us that G is quantized in units of $e^2/\pi\hbar$ in agreement with experimental observation.

This discovery may have great impact in use of ever decreasing electronic devices, because we will have to rethink our understanding of electronics down there.

2.2 Quantization of heat flow

To perform this kind of experiment the scientists needed freely suspended devices, structures possessing full three-dimensional relief. Because of the complexity of the structures required, it took almost a decade to realize useful experiment [2,6].

Four holes [*black*] on figure 4 etched into a silicon nitride membrane defined and isolated thermal reservoir [*central green square*] suspended by four narrow bridges. One gold transducer [*yellow*] electrically heated this reservoir; the second measured its temperature. Thin superconducting films [*blue*] on the top of the bridges electrically connected the transducers to off-chip instrumentation but carried no heat. The reservoir therefore cooled only through the silicon nitride bridges, which were so narrow that they passed only the lowest-energy heat waves.

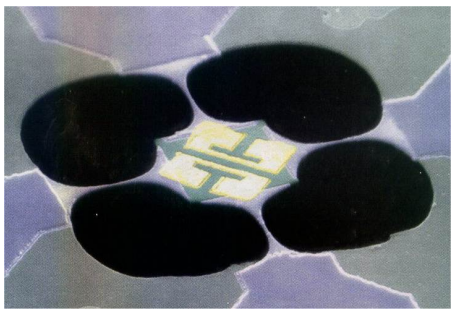

Figure 4: Nanobrigde device

We can write thermal flow through bridges with expression:

$$J_{th} = \sum_m \int_0^\infty \frac{dk}{2\pi} \hbar\omega_m(k) v_m(k) [\eta_{hot} - \eta_{cold}] T_m(k) \tag{7}$$

Here m is the mode index, $\omega_m(k)$ is the phonon dispersion relation for wave vector k, $v_m(k)$ is the group velocity, $\eta = [exp(\hbar\omega_m/k_BT) - 1]^{-1}$ are Bose-Einstein occupation factors for the two (hot/cold) thermal reservoirs connected by the phonon waveguides, and $T_m(k)$ are transmission coefficients characterizing the coupling of the wave guides to these reservoirs. This coefficient depends strongly on the connection of the reservoir and the bridge. If the transition would be too sharp, some of phonones would bounce of the connection and T would be smaller than 1. Thatswhy they etched round holes instead of very sharp squared ones. As for the case with electrons, conversion to an integral over energy, $\hbar\omega$, leads to a cancellation between the density of states $\frac{\partial k}{\partial \omega_m}$ and the modal group velocity $v_m(k)$. In the limit of linear response, $\Delta T \ll T$, the resulting expression for thermal conductance depends only upon $T_m(\omega)$, the mode thresholds at k=0 , and the fundamental constants:

$$G_{th} = \frac{J_{th}}{\Delta T} = \frac{k_B^2}{h} \sum_m \int_{x_m}^\infty dx \frac{x^2 e^x}{(e^x - 1)^2} T_m(x k_B T/\hbar) \tag{8}$$

Here, ΔT is the small, steady-state temperature difference between reservoirs that sustains J_{th} and $x_m = \hbar\omega_m(k = 0)/k_BT$.

This expression becomes greatly simplified in the limit $k_BT \leq \hbar\omega_m$, where only the four lowest lying, massless modes (that is, having zero threshold, $\hbar\omega_i(k = 0) = 0$) make an appreciable contribution. These four lowest modes arise from one dilatational, one torsional, and two flexural degrees of freedom. For ideal coupling between ballistic thermal conductor and the reservoirs, yielding modal transmission coefficients, T_m, equal to unity (shape of the connection between reservoir and the bridge), a fundamental relation holds for each mode,

$$G_{th} = g_o = \pi^2 k_B^2 T/(3h) \tag{9}$$

an expression devoid of any material parameters. This quantum of thermal conductance, $g_0 = (9.456 \times 10^{-13} W/K^2)T$, Represents the maximum possible value of energy transported per phonon mode.

By electrical conductance quantum, we could separately control temperature and chemical potential, so it was possible to sweep the edge of the sharp electron distribution function (constant temperature 0.6 K) through one-dimensional modes. With phonons, only the temperature could be swept; at low temperatures only the lowest lying modes make the contribution. On the plot on figure 5 one can observe transition from linear regime (ratio in close to unity)to cubic regime, which is predicted for lower temperatures. This law is some kind of completion of cubic law for very low temperatures (under 1 mK)

This quantum is a significant parameter for nanoelectronics; it represents the ultimate limit for the power-dissipation problem. In brief, all "active" devices require a little energy to

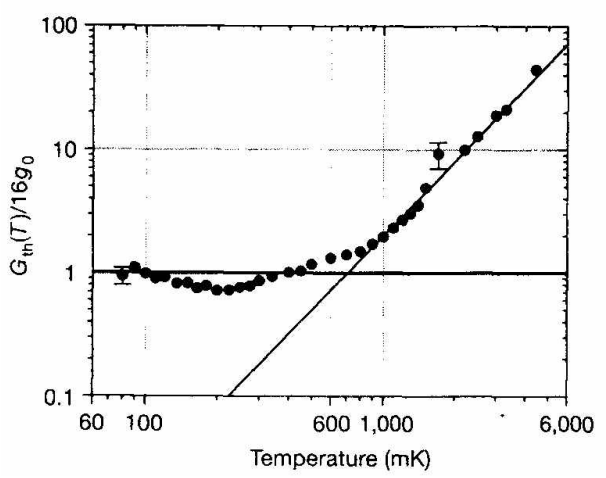

Figure 5: Thermal conductance data, normalized by the expected low-temperature value for 16 occupied modes; 4 bridges and 4 lowest modes

operate, and for them to operate stably without overheating, we must design a way to extract the heat they dissipate. As engineers try to ever increase the density of transistors and the clock rates (frequencies) of microprocessors, the problem of keeping microchips cool to avoid complete system failure is becoming monumental. This will only become more relevant in nanotechnology.

2.3 Single electron electronics

Advances in nanofabrication allowed Theodore A.Fulton and Gerald J.Dolan to build a single-electron transistor at Bell Laboratories in 1987 [*micrograph*] [2]. In this structure the controlled movement of individual electrons through a nanodevice was first achieved. At its heart was a *coulomb island*, a metallic electrode isolated from its counter-electrodes by thin insulating oxide barriers [diagram on figure]. The counter-electrodes led up to the macroscale laboratory instrumentation used to carry out the experiments. An additional gate electrode (visible on the diagram of figure but not the micrograph) was offset from the coulomb island by a small gap; it allowed direct control of the charge introduced to the island. Electric current flowed through the device from one counter-electrode to another, as in a conventional circuit, but here it was limited by the stepwise hopping of electrons onto off the coulomb island.

Fulton and Dolan's experiments demonstrated both the fundamental physics of single-electron charging and the potential use of these devices as ultrasensitive electrometers: instruments that can easily detect individual electron charges. Circuits that switch one electron at a time could some day form the basis for an entirely new class of nanoelectronics. The advent of such single electronics, however, also presages problems that will have to be faced as conventional electronic circuits are shrunk to the nanoscale.

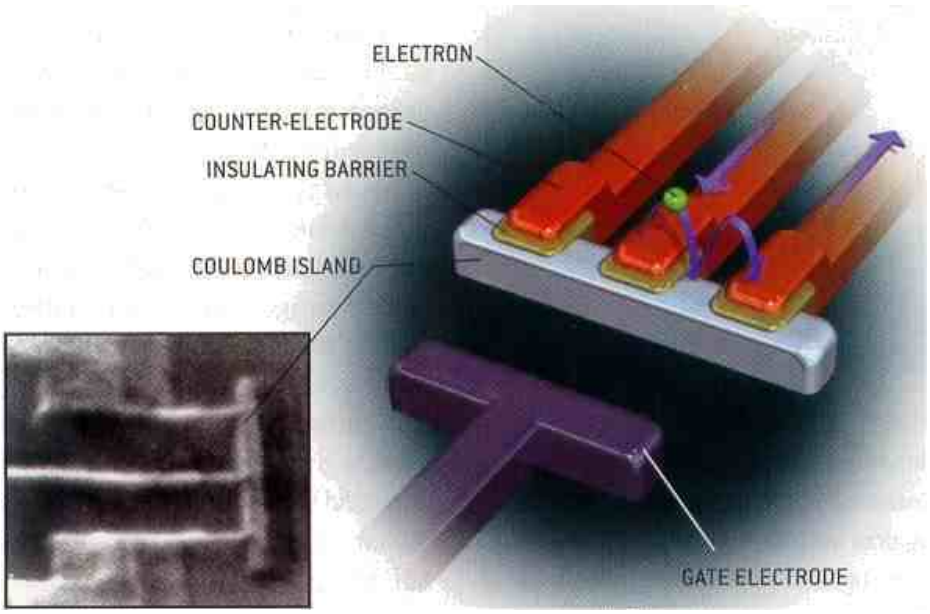

Figure 6: Single electron micrograph

3 Ways of fabrication

There are two basic ways of producing small objects: *top-down* and *bottom-up* fabricating. The first method begins with pattern generated on larger scale and reduces its lateral dimensions (often by factor 10) before carving out nanostructures. The second method starts with atoms and molecules and builds *up* to nanostructures. Current microelectronics rests on techniques that routinely fabricate structures as small as 100 nanometers across. This size is tiny by the standards of everyday experience, but it is large on the scale of atoms and molecules. The diameter of a 100-nanometer-wide wire span about 500 atoms of silicon. The most frequently used technique in mass-production is *photolithography*[3].

3.1 Photolithography

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.

First, consider the advantages and disadvantages of photolithography, which is basically an extension of photography. One first makes the equivalent of a photographic negative containing the pattern required for some part of 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 cresting 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 that can be slow and expensive) and the use of the mask to manufacture replicas (which must be rapid and inexpensive). Why not use photolithography to make nanostructures? The technology faces

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 section 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-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.

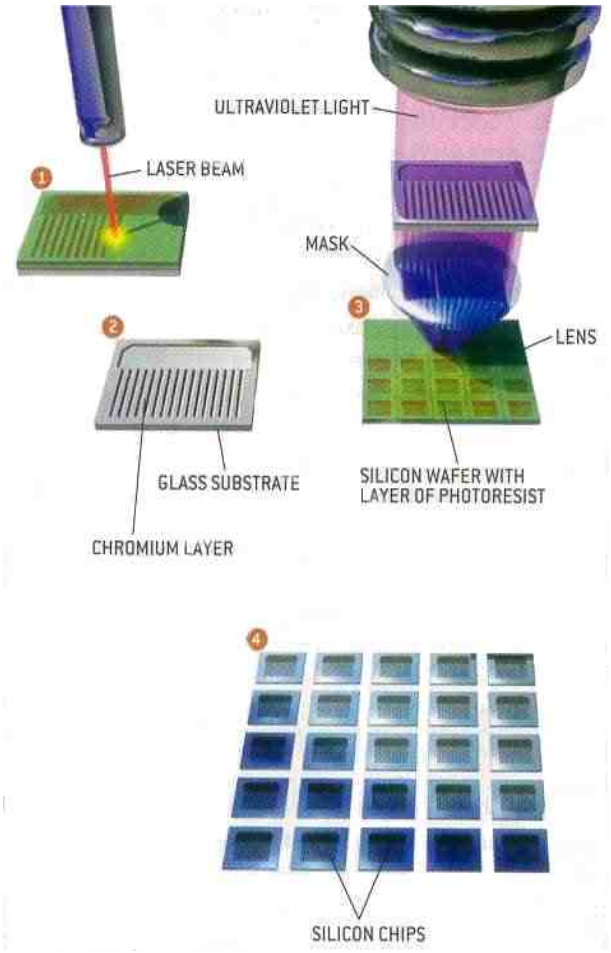

Figure 7: Scheme of main steps in conventional photolithography

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 the spacing is like trying to read print that is 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 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, material scientists, chemists and physicists who wish to explore nanoscience using structures of their own design.

To make a mask for 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 of silica). Photolithography then reduces the size of the pattern in a process analogous to that used in a photographic darkroom [scheme on figure 7 on page 10] beam of light (typically ultraviolet light from mercury arc lamp) shines through the chromium mask, than passes through a lens that focuses the image onto a photosensitive coating or organic polymer *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.

Improvements in photolithography

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.

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 the features. Researchers have used this technique to write lines with widths of only a few nanometers in layer of photoresist on 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 is *lithography using x-rays* with wavelengths between 0.1 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 ny diffraction. This 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.

Obviously described alternatives or improvements aren't as promising as hoped. Therefore the research continuous and unconventional approaches that haven't been explored yet are in front.

3.2 Soft lithography

This new method has developed from well-known manufacturing of microfluidic systems-chips with channels and chambers for holding liquids used in biochemistry [3].

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 than are familiar in everyday life: *printing, stamping, molding,* and *embossing*. The techniques are called soft lithography because the the tool they have in common is a block of *polydimethylsiloxan* (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 ar 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 the silicon wafer. This process generates a bas-relief master in which islands of photoresist stand out of the silicon [illustration on figure 8 on page 12]. Then a chemical precursor to PDMS-a free-flowing liquid-is poured over the bas-relief master and cured into the rubbery solid.

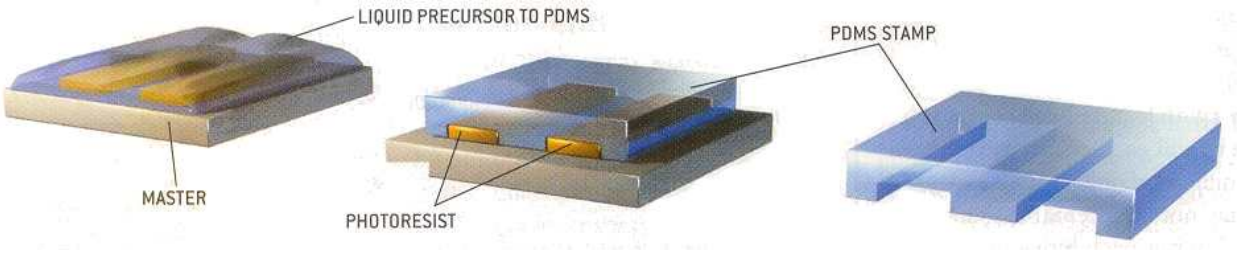

Figure 8: Making an elastic stamp

1. A liquid precursor to polydimethylsiloxan (PDMS) is poured over a bas-relief master produced by photolithography or electron-beam lithography.
2. The liquid ic cured into a rubbery solid that matches the original pattern.
3. The PDMS stamp is peeled of the master.

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

3.2.1 Microcontact printing

The first metod[1] is called *microcontact printing*. The PDMS stamp is "inked" with a reagent solution consisting of organic molecules called thiols [scheme on figure 9 on page 13]. The stamp is than brought into contact with an appropriate sheet of "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 by quite as high as that of the PDMS stamp. But when used correctly, microcontact printing can produce patterns with with features as small as 50 nanometers.

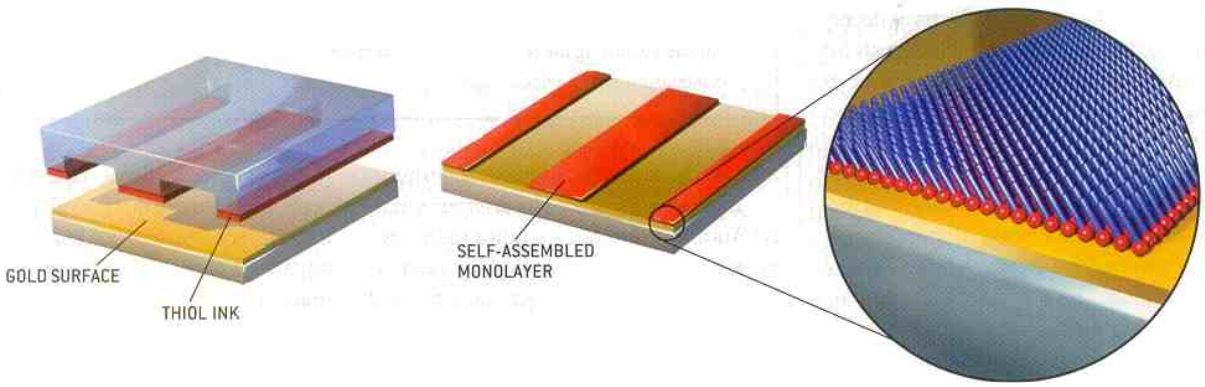

Figure 9: Microcontact printing

1. The PDMS stamp is inked with a solution consisting of organic molecules called thiols and then pressed against thin film of gold on a silicon plate.
2. The thiols from a self-assembled monolayer on the gold surface that reproduces the stamp's pattern; features in the pattern are as small as 50 nanometers.

3.2.2 Micromolding in capillaries

Another method of soft lithography, called micromolding in capillaries, involves using the PDMS stamp to mold patterns. The stamp placed on a hard surface, and a liquid polymer flows by capillary action into recesses between the surface and the stamp [scheme on figure 10 on page 14]. The polymer then solidifies into desired pattern. This technique can replicate structures smaller than 10 nanometers. It is particulary 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 are in

[1] originally developed by Amit Kumar, a postdoctoral student from Harvard University

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.

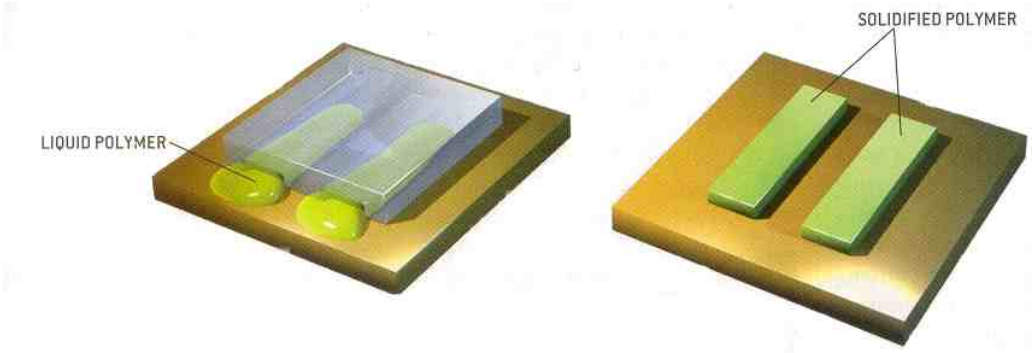

Figure 10: Micromolding in capillaries

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.

3.2.3 Advantages and disadvantages

Described methods require no special equipment and in fact can be carried out by hand in an ordinary laboratory. Conventional photolithography must take place in 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 surface, the stamp will compress over the top of the particle but maintain contact with 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 pattern on curved 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 microelectronics 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 least in part-by employing a rigid stamp instead of an elastic one. In a technique called *step and flesh imprint lithography*[2]. Photolithography is used to etch a pattern into a quartz plate, yielding a rigid bas-relief master. Next step is not making of PDMS stamp from the master, instead the master himself is pressed against a thin film of liquid polymer, which fills masters recesses. Then the master is exposed to ultraviolet light, which solidifies the polymer to create the desired replica. A related technique called *nanoimprint lithography*[3], 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.

Some other possibilities in production of nanostructures are described in appendix A.

4 Conclusion

Nanotechnology may be the beginning of a new era. Nanorobots would be able to assemble any arbitrary objects and perform tasks on nanoscale. That ability would revolutionize industry because no complex procedures would be necessary and there would be no waste that is often poisonous. Pollution-free simplified production is not all - we could even de-pollute nature in air, ground and water. Perhaps the most radical and dreamlike revolution would emerge in medicine: all the diseases would be defeated, we could maintain youthful bodies practically forever and so stretch life spans almost indefinitely. This godlike control over physical world has also its dark side. I would not dare to even think of disastrous outcomes if something would go wrong or if it would be used in even purposes.

(Un)fortunately we are just at the beginnings of the nanotechnology. In this seminar I have discussed perhaps the most important issue in this field: the building of nanostructures. It is obvious that we are able to manufacture only the very rudimentary objects that are far from something like mentioned nanorobots. Some of the possible use of nanotechnology in practice is described in appendix B.Eventhough this research is still quite fundamental, nanotechnology is here but what the future brings is yet to be seen.

[2]developed by C. Grant Willson of the university of Texas

[3]developed by Stephen Y. Chou of the Princeton University

5 Literature

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A Some other building techniques

A.1 Two-dimensional arrays of atoms

Perhaps the most obvious way of building simple two-dimensional structures is just by pushing atoms around. This approach is possible since the invention of scanning probe devices: scanning tunneling microscope (STM) and atomic force microscope (AFM) [3].

The operating principle of the AFM is similar to the old-fashioned phonograph. A tiny probe-a fiber or a pyramid-shaped tip [figure 11]that is typically between 2 and 30 nanometers wide-is brought into direct contact with the sample. The tip 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.)

STM is actually a device that is able to detect small currents that pass between the microscope's tip and sample being observed, allowing researchers to "see" substances at the scale of individual atoms. If researchers increase the current flowing from the tip of the STM, the microscope becomes a very small source for an electric beam, which can be used to write nanometer-scale patterns. The STM tip can also push individual around on a surface to build rings and wires that are only one atom wide.

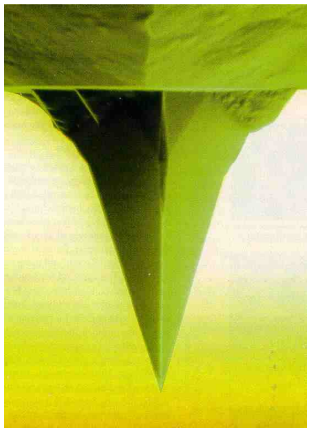


Figure 11: Tip of the AFM

A.2 Dip-pen lithography

This intriguing method works much like a goose-feather pen [3]. 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 a 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 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 dip-pen method for precise modifications of circuit design.

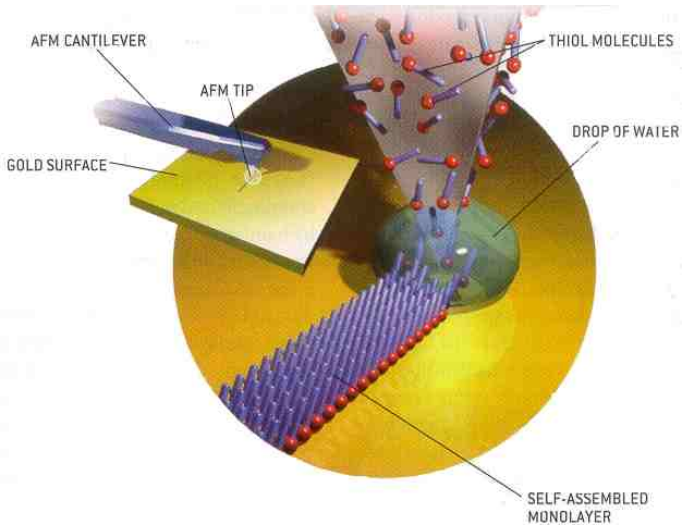


Figure 12: Dip-pen lithography

A.3 Break junction

Another interesting technique involves another kind of nanostructure, called *a break junction* [3]. 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 the wire. When the wire is slender enough, current can flow only in discrete quantities (that is current flow is quantized)

Break junction was the essence of an experiment [4], in which researchers were able to measure a current flowing across the organic bridge. This experiment was an important stem the development of technologies for using single organic molecules as electronic devices such as diodes and transistors.

A.4 Bottom-up methods

All the forms discussed so far are actually top-down methods, because all of them start with big chunks of material, which are in some way reduced to nanoscale [3]. 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. This methods can easily

[4] the experiment was conducted by Mark A. Reed of Yale University

make the smallest nanostructures - with dimensions between two and ten nanometers - and do so inexpensively. But these structures are usually 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.

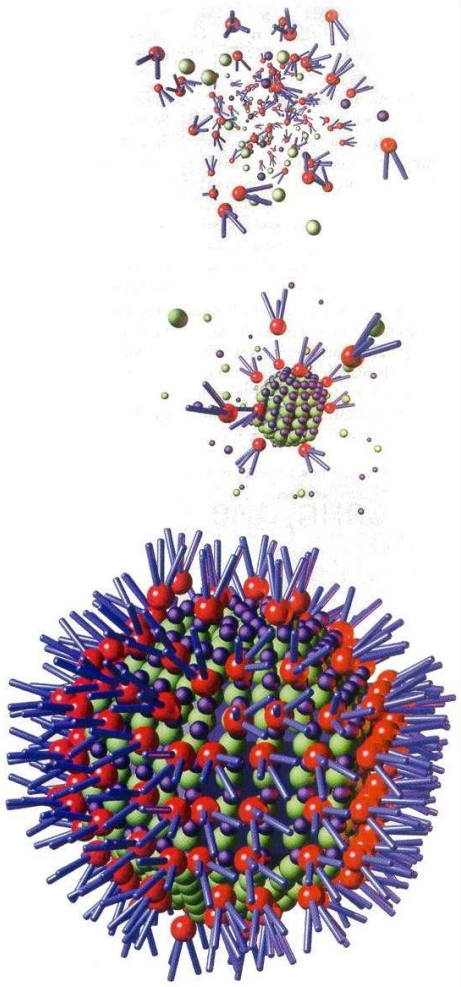


Figure 13: Quantum dot assembly

Quantum dots are metal 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[figure 14 on page 20]. One procedure [figure 13]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 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. It is important to synthesize the quantum dot 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 surface of the crystals.

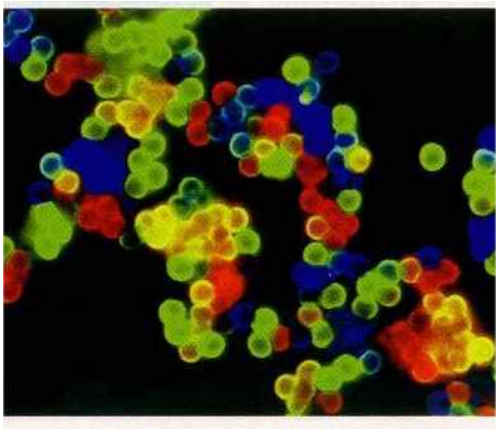


Figure 14: Quantum dots

Scientists are also investigating the possibility of making structures from colloids - nanoparticles in suspension. The IBM team's colloids contain magnetic nanoparticles as small as three nanometers across, each composed of about 1000 iron and platinum atoms. When the colloid is spread on the surface and the solvent allowed to evaporate, the nanoparticles crystalize 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.

B Potential use of nanotechnology

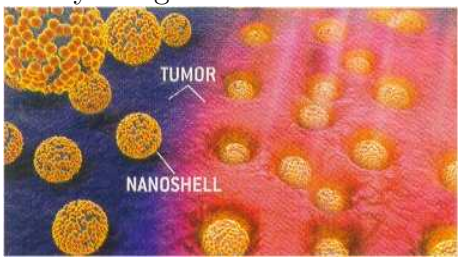
The first scientists that were confronted with limits of nanoworld were producers of electrical circuits. Current microelectronics involves components that measure roughly one micron on a side (although lately the components have shrunk to a size of almost 100 nanometers). Going beyond microelectronics means more than simply shrinking components by a factor of 10 to 1000. It also involves a paradigm shift for how we think about putting everything together. Nevertheless lithographic techniques enable production of smallest silicon chips, but that procedure still doesn't have the precision for devices that are mere nanometers in width.

More revolutionizing is the idea of building small microelectromechanical systems (MEMS), whose structures measure in terms of microns. The goal is to develop MEMS robots that would be able to pick up and precisely place objects into assembly. Self- replicating nanomachines could produce virtually any material good, while reversing global warming, curing disease and dramatically extending live spans. We are far from being able to produce robots with described properties. Objects that can be build are very rudimental and are still in experimental phase [4].

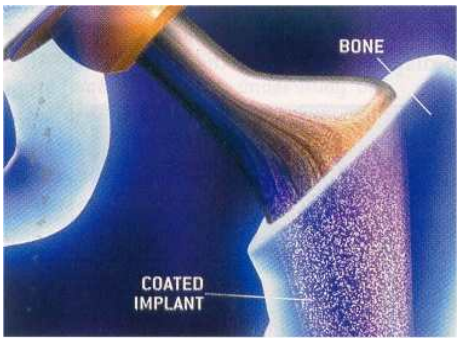
Research in medicine is perhaps the nearest in terms of efficient use of nanostructures. Main goals, or "grand challenges," include a host of futuristic improvements in the detection, diagnosis and treatment of disease. The goals, many of which are far from being realized, also feature new aids for vision and hearing, rapid tests for detecting disease susceptibility and responses to drugs, and tiny devices able to find problems-such as incipient tumors, inflections or heart problems-and to relay the information to an external receiver or fix them on the spot.

Improved or new contrast agents would detect problems at earlier, more treatable stages. They might, for instance, reveal tumor [*red*] only a few cells in size.

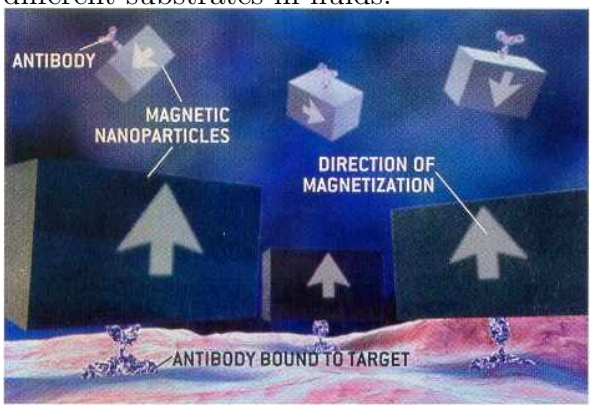
Nanoparticles would deliver **treatments** to specifically targeted sites, including places that standard drugs do not reach easily. For example, gold nanoshells [*spheres*] that were targeted to tumors might, when hit by infrared light, heat up enough to destroy the growths.



Nanometer-scale **modification of implant** surfaces would improve implant durability and biocompatibility. For instance, an artificial hip coated with nanoparticles might bond to the surrounding bone more tightly than usual, thus avoiding loosening.

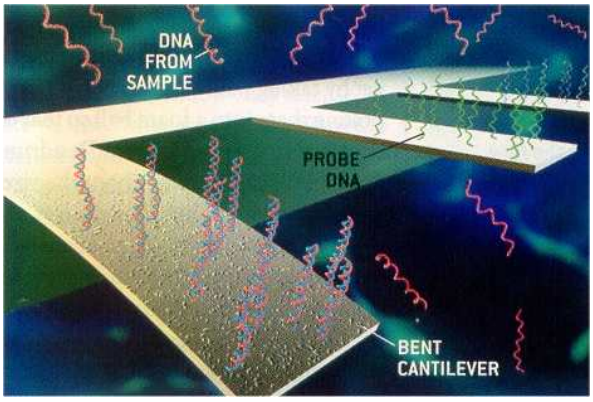


Another important goal is also to improve and simplify detection and identification of different substrates in fluids.



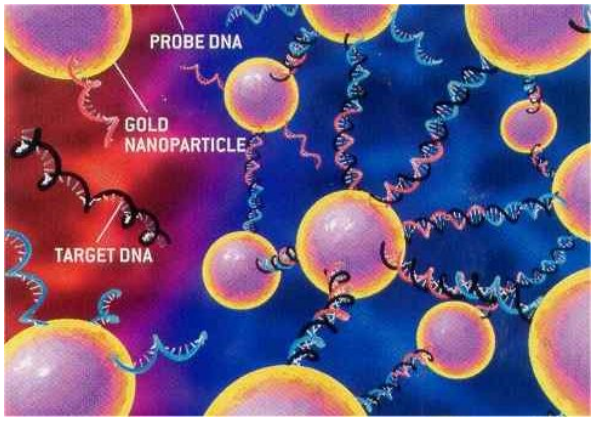
Magnetic tags

When antibodies labelled with magnetic nanoparticles bind to their target on surface [*foreground*], brief exposure to a magnetic field causes these probes collectively to give off a strong magnetic signal.



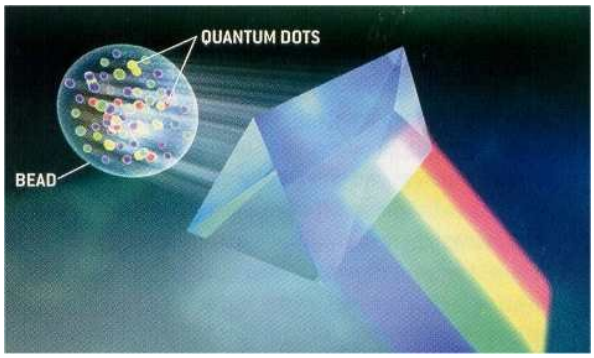
Clever cantilevers

The surface of each cantilever is coated with DNA able to bind one particular target sequence. A sample is than applied to the beams. Binding induces a surface stress, which bends the affected beams by nanometer-not much but enough to reveal that the bent beams found their specific target in the sample.



Gold particles

Both sequences of DNA [*red and blue*] are attached to two sets of particles in solution. If the sequence [*black*] of interest is present in the sample, it will bind to the DNA tentacles on both spheres, trapping the balls in a dense web. This agglomeration will cause the solution to change color [*from red to blue*].



Nano bar codes

Latex beads filled with quantum dots [*nanoscale semiconductors*] can serve as labels for different probes. In response to light, the beads would identify themselves [and their linked probes] by emitting light that separates into a distinctive spectrum of colors and intensities-a kind of spectral bar code.

As described, nanotechnology, is still in the research phase, but some nanoparticles are ready to enter in the industry. For example drying and softening agents, catalysts for different reactions in fabrication processes, nanostructures for detection and filtration of poisonous substances in water. New progress is also achieved in search for better batteries, smart glass, storing hydrogen in nanotubes etc.

The actual question is how build nanoparticles and more complex structures cheaply and effectively so that nanofabrication would develop to mass production.