Big Future for Tiny Dies

NANOIMPRINT LITHOGRAPHY PROMISES A REVOLUTIONARY ADVANCE IN NANOTECHNOLOGY

BY STEPHEN Y. CHOU

In the world of transistors and computer chips, small is everything. The smaller the transistors, the faster and cheaper they are, the less power they consume, and the more of them can be packed into a chip for more computation power. Since the invention of integrated circuits in 1960, every six years the transistor size has halved and the number of transistors per chip has quadrupled (so-called Moore's law). Small is also the soul of the intriguing, fast-growing field of nanostructures. As the structure size becomes smaller than some fundamental physical length scales, conventional physics theory may no longer apply, leading to new opportunities for innovation and discovery.

A die can be used on a lithographic resist to impress structures 20 times smaller than can be achieved photographically. Professor Stephen Chou of the University of Minnesota explains how it is done and considers prospective applications.

Nevertheless, despite their promise demonstrated in the laboratory, most [illegible]percomputer chips and innovative nanostructures with dimensions smaller than 100 nm are currently too expensive to be produced commercially. The key problem has been the lack of a low-cost and high-throughput lithography for producing such small structures.

Things started changing two years ago, when a new lithographic paradigm, nanoimprint lithography, was demonstrated. Nanoimprint lithography has achieved feature sizes of 10 nm, a pitch size of 40 nm, and excellent uniformity in an area of about 6 cm^2 (1 square inch). Studies indicate that with further development, nanoimprint lithography will be able to fabricate and replicate even smaller feature sizes (<10 nm) over a large area, with high throughput and at low cost—a feat impossible using existing lithographic methods. Such technology will open up many opportunities for commercial application, not only in microelectronics, but also in data storage, biology, chemistry, chemical engineering and medicine, to name a few areas. Moreover, nanoimprint lithography may play the role that personal computers served in the computer industry—making nanostructures accessible for everyone, accelerating nanostructure research and triggering avalanches of innovations. Many of the innovations may be beyond our current imagination.

CONVENTIONAL LITHOGRAPHY

Lithography is a process in which a thin film (called a resist) is applied to a substrate and is patterned. In a subsequent process, the substrate surface unprotected by the resist is modified (e.g. by being etched away or by the addition of a new material on top of it) but the protected surface remains the same, transferring the pattern from the resist into the substrate. Lithography was invented in 1796 by Alois Senefelder, a German actor-turned-printer, as a method to create the plates for printing; the word is derived from the Greek words λιθοσ (lithos = stone), and γραφειν (graphein = to write), since Senefelder used limestone as the substrate and wrote with a grease pencil to apply and pattern the resist.

In the lithography used today for making computer chips and other micro- and nanostructures, a thin radiation-sensitive polymer (the resist) is cast on a substrate and is patterned by exposing some

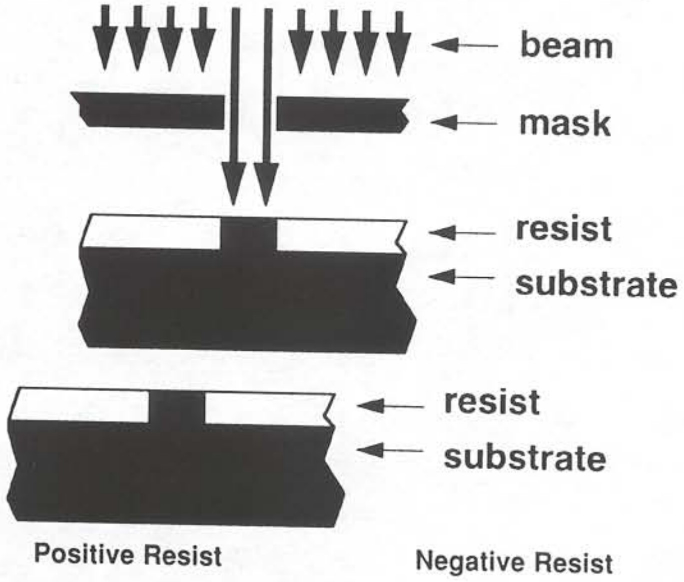


Figure 1: Schematic of conventional lithography where radiation changes the solubility of a resist.

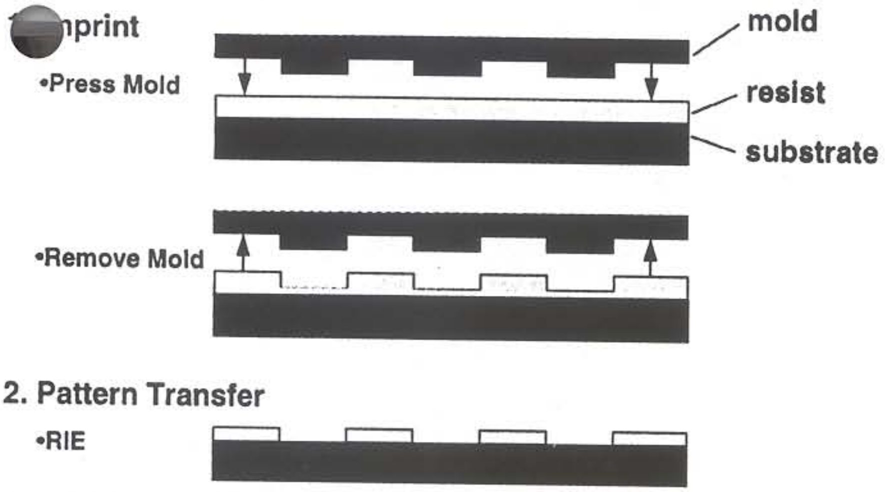


Figure 2: Schematic of the nanoimprint lithography process: (1) imprinting using a mold to create a thickness contrast in a resist; and (2) pattern transfer using anisotropic etching to remove residue resist in the compressed areas.

areas of the resist to particle radiation, such as photons, electrons or ions. The radiation alters the chemical structure of the exposed area and hence changes its solubility in a developer solvent (Figure 1). For a positive resist, the exposed area is removed in the developer, while for a negative resist, the unexposed area is removed. A resist can be selectively exposed either in parallel by sending a flood of particles through a mask that contains the desired image, or in series by writing a point at a time with a focused particle beam. One advantage of patterning by lithography over other patterning methods (such as self-assembly) is that, in principle, lithography allows for complete freedom in designing the size, shape, and spacing of the pattern. Such freedom is essential in many innovative applications.

The minimum feature size (often called the resolution) achievable with conventional lithography depends on a number of factors: the wavelength of the radiation used, the scattering and interference of particles in the resist, the backscattering of the particles in the substrate, the resist properties and the developer chemistry.

Optical lithography, which dates back over 160 years, is still the primary tool used to manufacture computer chips because of its low cost compared with other lithography approaches. State-of-the-art optical lithography using 248-nm wavelength light (deep ultraviolet) can pattern a feature as small as 250 nm in the resist. The size is limited by the wavelength of light. Industry expects to use 193 nm wavelength optical lithography to manufacture 130 nm size features in the year 2004. However, for light with a wavelength shorter than 193 nm, glass materials that are transparent in the visible and near UV are opaque; thus a fundamental change in lithography tool design will be required. Whether optical lithography can produce structures smaller than the 130 nm feature size is unclear.

Scanning electron beam lithography, invented 60 years ago, has demonstrated a resolution of 6 nm. Since it exposes a point at a time, it has a very low throughput, and is used mainly for producing masks for optical lithography. To pattern 250-nm features (e.g. a dot array) covering a 15 cm (six inch) diameter wafer would take 100 to 1,000 times longer with state-of-the-art electron beam lithography than with an optical lithographic tool. Governed by electron optics, the throughput of electron-beam lithography diminishes quickly as the minimum feature size gets smaller. Since an e-beam lithography system costs at least $5 to $10 million, it is economically impractical to mass-produce sub-100 nm structures using current e-beam lithography systems.

X-ray lithography, originated in the 1970s, has a demonstrated 20-nm resolution. Seemingly a natural extension of optical lithography, X-ray lithography, because of the short wavelength of the radiation used, actually requires very different technologies to generate and focus enough photons and to make high-fidelity masks. Those technologies are very expensive. For instance, the cost of a synchrotron radiation ring plus exposure station and necessary safety protection equipment can easily be tens of millions of dollars.

Devised in the late 1980s, lithographies based on scanning proximal probes have showed a 10-nm resolution. But they are in the early stages of development. Thus, no existing lithographies based on modification of polymer chemical structure can, at present, fabricate sub-100-nm structures with high throughput and low cost.

NANOIMPRINT LITHOGRAPHY

Fundamentally different from conventional lithography, nanoimprint lithography, originated in 1994, patterns a resist by deforming it with a mold, rather than by changing the chemical structure (and solubility) using radiation. More specifically, nanoimprint lithography consists of two steps: (a) the imprint step, in which a mold with nanoscale features is pressed into a resist film cast on a substrate, creating a thickness contrast pattern in the resist; and (b) the pattern transfer step, in which an anisotropic etching process (i.e. etching in the vertical direction much faster than that in the lateral direction) is used to transfer the pattern through the entire thickness of the resist by removing the remaining resist in the compressed areas (Figure 2). During the imprint step, the resist, a thermal plastic, is heated to a temperature above its glass transition temperature, becoming a viscous liquid that can

Figure 3: Scanning electron microscopy (SEM) image of a 10 nm diameter and 40 nm period hole array imprinted in polymethyl methacrylate (PMMA).

Figure 4: SEM image of a profile of strips formed into a PMMA film by the imprint technique. The strips are 70 nm wide and 200 nm tall, have a high aspect ratio, a surface roughness of less than 3 nm, and nearly perfect 90 degree corners.

flow and easily be deformed to the shape of the mold. In a sense, nanoimprint lithography patterns a resist the way a cookie cutter cuts rolled out dough. Unlike conventional lithography methods, nanoimprint lithography does not use any energetic beams and does not alter resist chemical property, so its resolution is not limited by many of the problems encountered in conventional lithography.

Figure 3 shows an array of 10-nm-diameter holes with a 40-nm period in polymethyl methacrylate (PMMA) imprinted with a silicon dioxide mold at a 150° C temperature and a 4 MPa pressure. The hole depth is 60 nm, determined by the intrusion of the mold. The initial PMMA thickness was 75 nm—thicker than the intrusion of the mold, so that the mold would not touch the substrate, which is essential to increase the mold's lifetime. A typical sidewall profile of imprinted PMMA is shown in Figure 4. It has very smooth (roughness less than 3 nm), vertical sidewalls, and nearly 90° corners. Comparison of the imprinted PMMA with the mold indicates that the PMMA profile conforms to the mold.

To check if the reactive ion etching used in the pattern transfer step reduces the lateral dimension of the PMMA features, the PMMA resist structures created by imprint lithography were used as the template for lifting off metals. In the liftoff process, 5 nm titanium and 10 nm gold films were first deposited onto the entire sample, and then the metal on the PMMA surface was removed when the PMMA was dissolved in acetone. Hence the metal left on the substrate represents the foot-print of the mold. Figure 5 shows 10-nm-diameter metal dots with a 40-nm period, made by a lift off method using the PMMA template of 10-nm-diameter holes shown in Figure 3. Figure 6 shows 15-nm-wide metal lines with 60-nm-period, made by lift-off techniques. Comparison of these metal features with the imprinted PMMA templates before the pattern transfer step reveals no noticeable differences between the liftoff metal structures and the PMMA patterns. This indicates that, during the process of etching with reactive oxygen ions, the compressed PMMA areas were completely removed while the

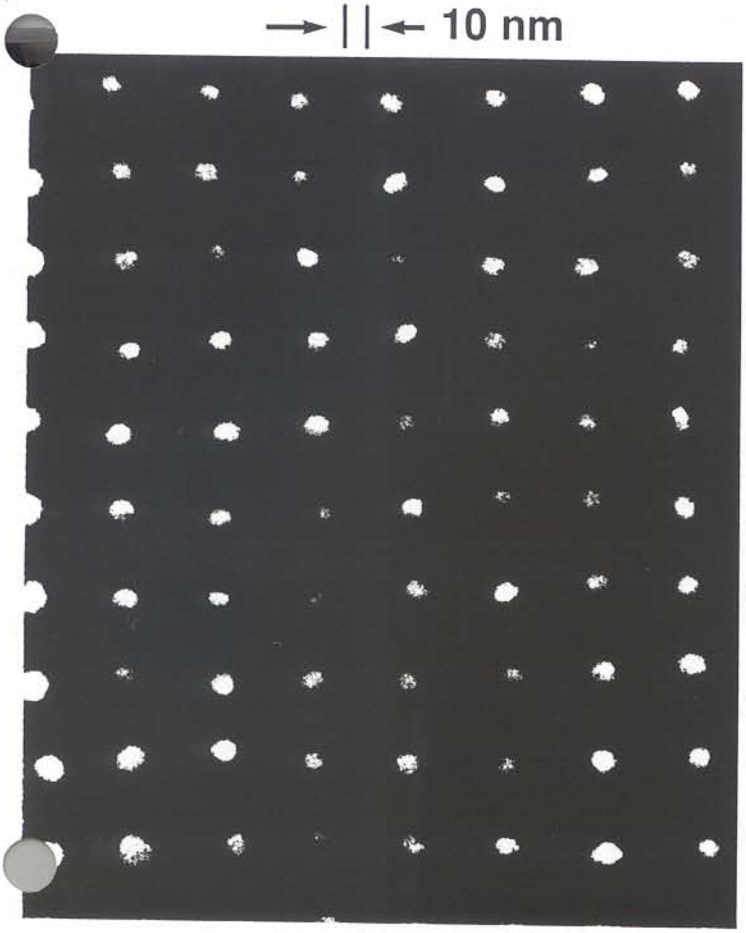


Figure 5: SEM image of 10 nm diameter and 40 nm period metal dots on silicon, fabricated using a lift off process with the PMMA shown in Figure 3 as the template.

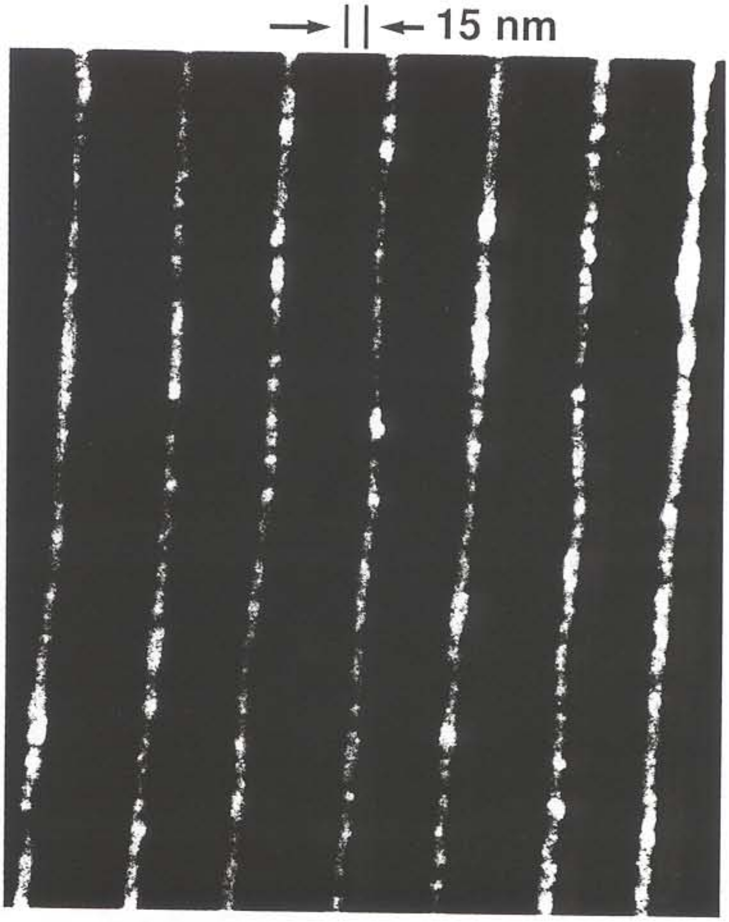
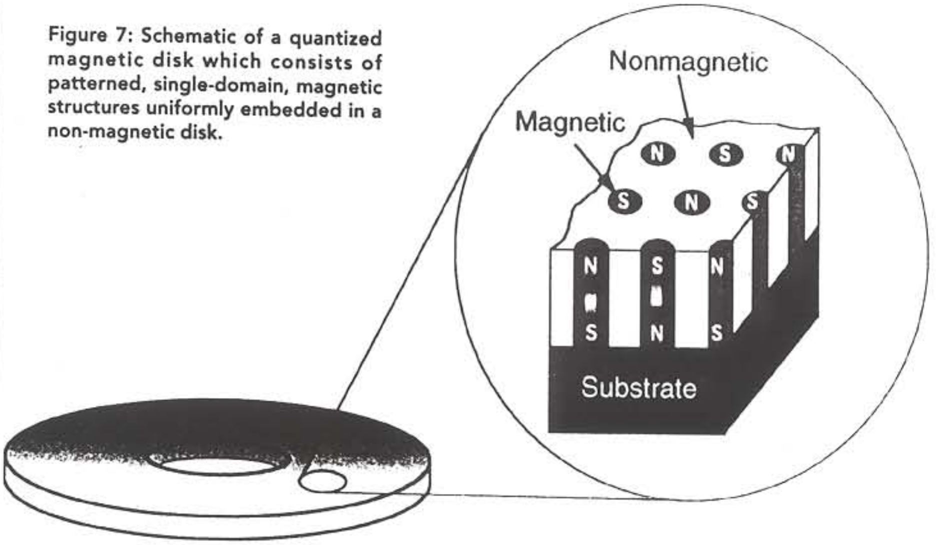


Figure 6: SEM image of 15 nm wide and 60 nm period metal lines fabricated by imprint lithography and a lift off process.

lateral size of the PMMA features experienced little change.

The minimum feature size of imprint lithography demonstrated here is limited by the minimum feature size on the current molds. The molds were fabricated using electron-beam lithography. Further experiments have shown that a variation of a few nanometers on the mold can be transferred successfully into the side walls of the PMMA. This means that if the polymer has sufficient mechanical strength, nanoimprint lithography should be able to produce features with sizes less than 10 nm. Furthermore, the nanoimprint lithography process has been found to be repeatable and the mold is durable. Uniform 30-nm-wide lines a 150-nm period over an area of 15 mm by

Figure 7: Schematic of a quantized magnetic disk which consists of patterned, single-domain, magnetic structures uniformly embedded in a non-magnetic disk.



18 nm have been achieved. It should be possible to expand the uniformity of the imprinted area, currently limited by the particular tools used in fabricating the mold, to areas of as much as 15 to 20 cm in diameter. Moreover, nanoimprint lithography has been used successfully to fabricate nanoscale silicon transistors.

BEYOND MICROELECTRONICS

As the only existing technology currently capable of fabricating structures of less than 10 nm in size over a large area with high throughput and low cost, nanoimprint lithography would greatly impact many fields—not only microelectronics, but also data storage, nanomaterials, chemistry, biology, and medicine. Since applications outside microelectronics often do not require multilayer alignment, they might be among the first to benefit from nanoimprint lithography. The following discussion covers a small sample of possible applications.

The first is the production of quantized magnetic disks. The data density of conventional magnetic disks is approaching the fundamental limit imposed by the properties of thin magnetic films. One way to overcome this limit is to replace the current disks with quantized magnetic disks (QMDs). In a QMD, the thin magnetic film is replaced by discrete, single-domain, magnetic structures (e.g. pillars) uniformly embedded in a non-magnetic disk (Figure 7). A magnetic structure can spontaneously become a single magnetic domain (like a permanent magnet) without an external field if its size is smaller than the wall size between two magnetic domains. (Depending upon the material, a domain wall is typically about 100 nm thick.) The shape anisotropy of the structure keeps the stable magnetization direction along its long axis, resulting in only two states for the element's magnetization: equal in magnitude, but opposite in direction. Each structure can represent a bit of binary information. QMDs have many advantages over conventional disks, such as much higher storage density and ease in writing, reading and tracking. However, such disks were regarded as "a pie-in-the-sky" because of the lack of a low cost

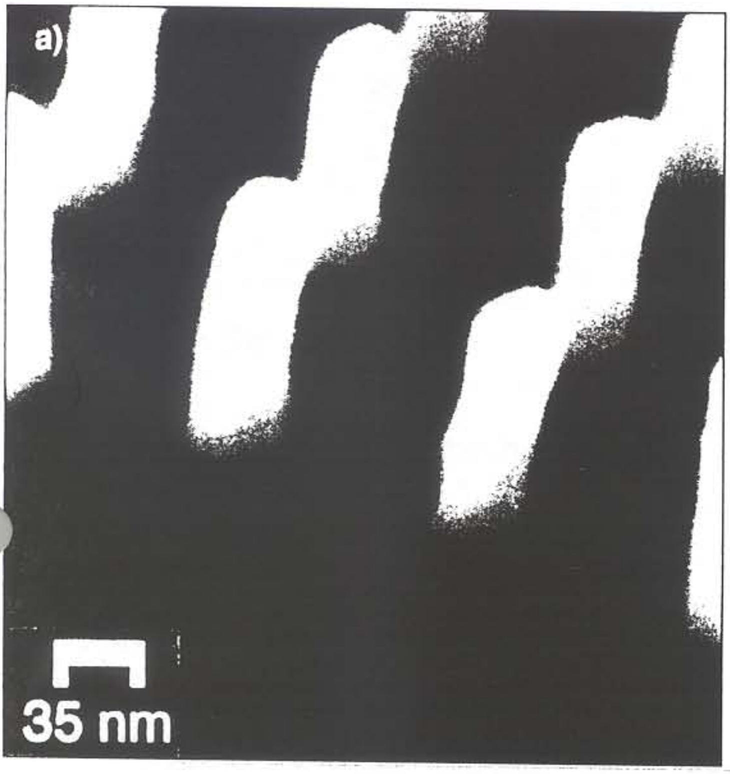
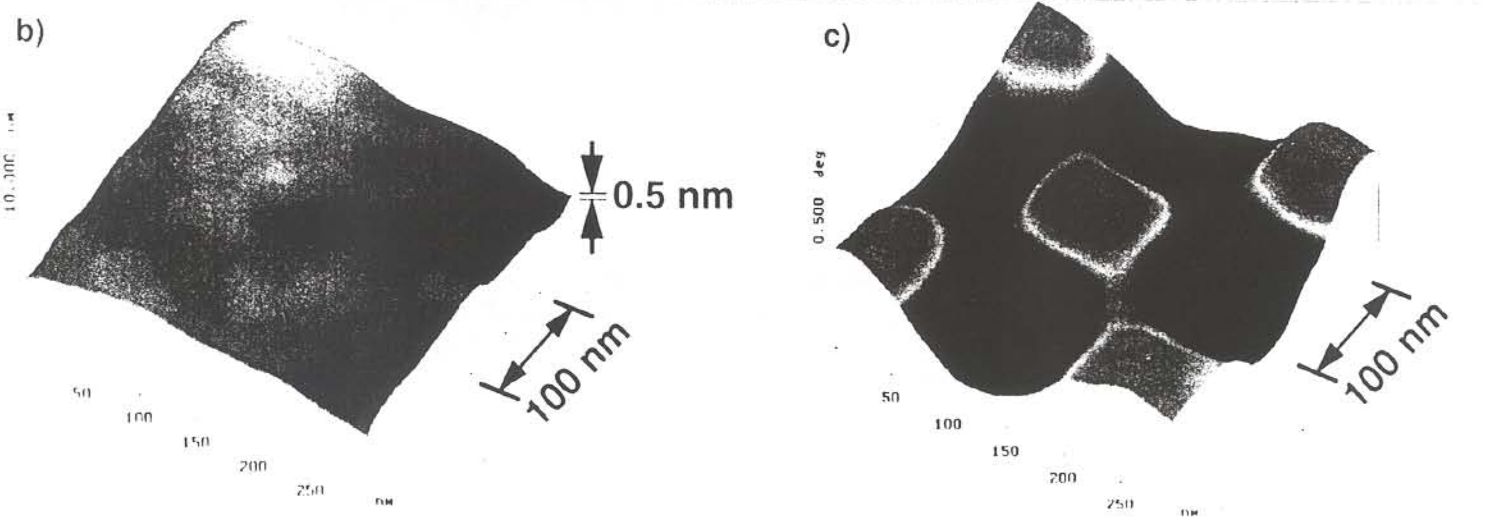
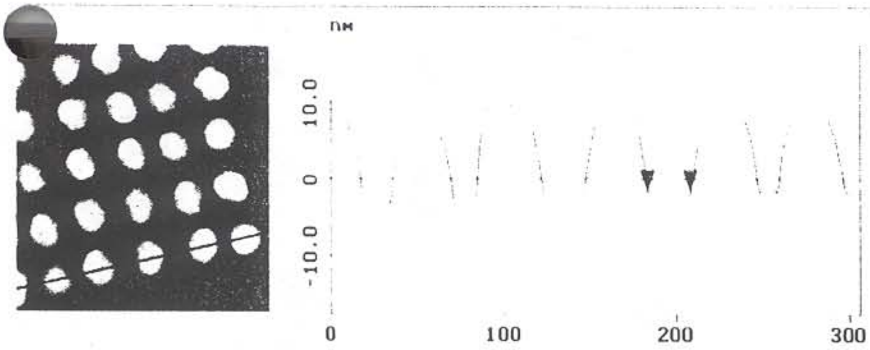
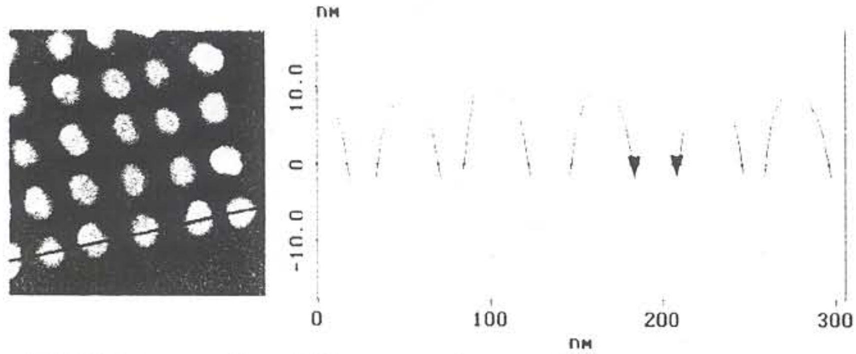


Figure 8: (a) SEM image; (b) tapping-mode atomic force microscopy (TMAFM) image; and (c) magnetic force microscopy (MFM) image of 3 by 3 bits of a QMD with 10 Gbits/cm^2 (65 Gbits/in^2) density. In the SEM, the oxide layer was removed to expose the Ni pillars. The TMAFM image shows a very smooth surface with a roughness of 0.5 nm (root mean square). In the MFM, the red represents the attractive force between tip and sample and the blue represents repulsive force.





Initial TMAFM image of 50 nm period nano-CD.



TMAFM image after 1000 scans of nano-CD

Figure 9: Atomic Force Microscope reading of a nano-CD with 62.5 Gbits/cm^2 (400 Gbits/in^2) density.

tterning technology for producing them. Nanoimprint lithography is well suited for fabricating QMDs. In fact, QMDs of 10 Gbits/cm^2 (1 Gbit = 10^9 bits) storage density, which is nearly two orders of magnitude higher than the current commercial disk, have already been demonstrated (Figure 8).

A second application is in nanoscale compact disks (nano-CDs). A current compact disk (CD) read-only-memory (ROM) has an outer diameter of 11.5 cm (4.6 inch), an inner diameter of 4.5 cm and a data storage capacity of 5.2 Gbits (a bit size of 0.83 µm, a track spacing of 1.5 µm, therefore a data density of 75 Mbit/cm^2). With shorter wavelength lasers emerging (particularly blue lasers), new CD ROMs in development will have a bit size and track spacing half that of current CDs and hence a data storage capacity of 20 Gbits in a 11.5 cm disk. Using nanoimprint lithography, a pattern density of 62.5 Gbit/cm^2 (400 Gbit/in^2) has been demonstrated, leading to four terabits in a 11.5-cm-diameter disk (Figure 9). This density, though not the highest that can be achieved using nanoimprint lithography, is nearly three orders of magnitude higher than that of current CDs. In other words, a nano-CD the size of a penny could hold data that would fill 30 conventional CDs, such as four hours of high-quality movies. Nano-CDs can be read using an atomic force microscope (AFM) tip. It was found that when using a tapping mode, both the AFM tip and the disk can be used for a long time without degradation, because the force between them is in the 0.1-10 nano Newton range (Figure 9).

A third application area is the creation of new nanomaterials, not only electronic materials, but also supramolecular materials. Nanoimprint lithography can create patterns on substrates, and can precisely control the size, shape, spacing, orientation and surface properties of the pattern. When the scale of the pattern becomes comparable to the fundamental physical length scales, such as the diffusion length or the supramolecule size, the pattern can uniquely "guide" the growth of other materials (organic or inorganic) on the substrate, leading to new materials that have unique properties not found in natural materials. The specific guiding is determined by the geometry and surface properties of the patterns put on a substrate, the so-called functionalization of a substrate.

One can confidently predict that nanoimprint lithography will also provide devices for use in subwavelength optics, displays, biology and medicine (e.g. special sieves for filtering DNA and bacteria, and the guided growth of biomaterials on a patterned substrate).

FUTURE CHALLENGES

Despite the demonstration of arrays of 10 nm feature size, 40 nm periods, and uniformity over several square centimeters, nanoimprint lithography is still in its infancy. Many technologies essential for turning it into a viable manufacturing method are not currently available. To advance nanoimprint lithography, developments in five areas are extremely critical: (1) nanoimprint machines; (2) mask technology (molds); (3) resist design and synthesis; (4) process development, metrology, and multilevel alignment; and (5) device applications using nanoimprint lithography. While tremendous challenges remain, many groups have started actively looking into this technology since the first report on nanoimprint lithography appeared in 1995. No doubt, significant progress in the development of this new technology and in its applications should be expected in the near future. Ⓢ

SUGGESTED READING

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