Nano-compact disks with 400 Gbit/in^2 storage density fabricated using nanoimprint lithography and read with proximal probe

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Nano-compact disks (Nano-CDs) with 400 Gbit/in^2 topographical bit density (nearly three orders of magnitude higher than commercial CDs) have been fabricated using nanoimprint lithography. The reading and wearing of such Nano-CDs have been studied using scanning proximal probe methods. Using a tapping mode, a Nano-CD was read 1000 times without any detectable degradation of the disk or the silicon probe tip. In accelerated wear tests with a contact mode, the damage threshold was found to be 19 μN. This indicates that in a tapping mode, both the Nano-CD and silicon probe tip should have a lifetime that is at least four orders of magnitude longer than that at the damage threshold. © *1997 American Institute of Physics.* [S0003-6951(97)04047-3]

Read only memory (ROM) disks are the most popular form of low-cost information storage media. Current ROM disks (also called Compact Disks) are made by injection molding, have a data storage density of ~ 0.68 Gbit/in^2, and are read using a focused laser beam. To meet the future demand for ROM disks with increasing information storage densities, methods must be developed for low-cost manufacturing of such disks with replicated data patterns, and for inexpensive read-back techniques suitable for retrieving high-density information. One promising approach is to develop ROM disks with ultrahigh-density topographical bits and to use proximal-probe based read-back. ROM disks of topographic bits with 45 Gbit/in^2 storage density have recently been demonstrated by a group from IBM.[1] In that work, features as small as 50 nm were produced by electron beam lithography and replicated on a glass substrate using a photopolymerization (2P) process. To further explore ultrahigh-density ROM disk technology, we have fabricated nano-compact disks with 400 Gbit/in^2 storage density containing 10 nm minimum feature sizes using nanoimprint lithography, and studied the reading and wearing of Nano-CDs using scanning proximal probe techniques. This storage density is nearly three orders of magnitude higher than commercial CDs (0.68 Gbit/in^2).

The Nano-CD fabrication process is based on nanoimprint lithography (NIL)—a high-throughput and low-cost nonconventional lithography technology with sub-10 nm resolution (Fig. 1).[2] NIL patterns a resist through deformation of resist physical shape by embossing rather than through modification of resist chemical structure by radiation or by self-assembly. The nanoscale topographical bits on a Nano-CD can be made with a variety of materials such as polymers, amorphous materials, crystalline semiconductors, or metals. Here, we focus our discussion on Nano-CDs consisting of metal bits.

In the first step of the Nano-CD fabrication process, a SiO_2 mold on a silicon substrate with a CD-like data pattern was fabricated using high-resolution electron beam lithography and reactive ion etching. The SiO_2 was selected because it has a low atomic number to reduce the backscattering and proximity effects during the electron beam lithography, thereby extending the lithography resolution down to features as small as 10 nm with a 40 nm period. Although high-resolution electron beam lithography is a relatively expensive and low-throughput process, the master mold may be used to replicate many Nano-CDs using inexpensive and high-throughput NIL. Furthermore, the master mold may be used to fabricate daughter molds, thereby increasing the total number of disks that can be fabricated per master mold, and lowering the cost per disk. The daughter molds may be composed of the same material as the master mold, or other materials (such as high atomic number materials) that are optimized for better durability performance. A daughter mold with 13 nm minimum feature size and 40 nm pitch fabricated using NIL is shown in Fig. 2.

The second step in the Nano-CD fabrication process was to imprint the mold into a polymer resist film on a disk substrate using NIL. The 75-nm-tall SiO_2 master Nano-CD mold was imprinted into a 90-nm-thick polymethylmethacrylate (PPMA) film on a silicon disk. During the imprint step, both the mold and resist coated disk were heated to 175 °C. The mold and wafer were compressed together with a pressure of 4.4 MPa for 10 min at this temperature, followed by being cooled down to room temperature. The mold was then separated from the disk resulting in duplication of the Nano-CD data pattern in the PMMA film. At this

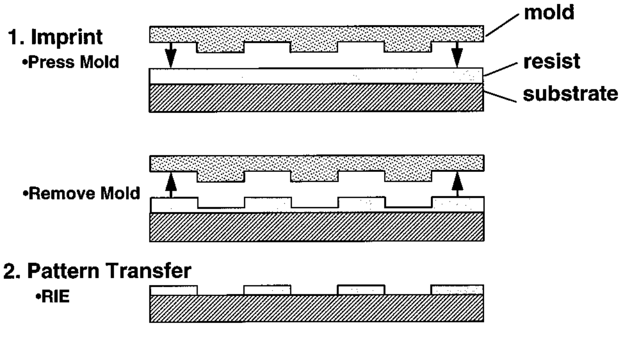

FIG. 1. Schematic of nanoimprint lithography process.

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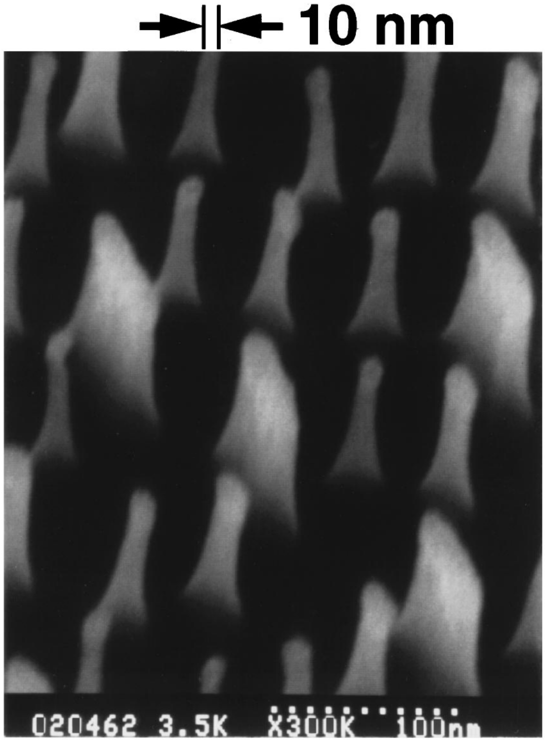


FIG. 2. SEM micrograph of a 50 nm track width Nano-CD daughter mold fabricated using nanoimprint lithography.

point, it is possible to directly use the disk with the patterned PMMA for data read-back, such as done with acrylate-based 2P processes.[1] The most important advantage of NIL over the 2P process is that it can produce smaller feature sizes. Another advantage is that the substrate choice in NIL is not limited to UV transparent materials such as glass, but can be silicon, aluminum, or other opaque substrates.

The third step of the Nano-CD fabrication process was to transfer the imprinted pattern into metal bits, which have much better durability than polymers during read-back. An anisotropic O_2 RIE pattern transfer step was used to transfer the imprinted pattern through the entire PMMA thickness. The resulting PMMA template was used to transfer the Nano-CD pattern into metal using a lift-off process where Ti/Au (5 nm/10 nm thick) were deposited on the entire disk and lifted off. Figure 3 shows a section of a Nano-CD with a 40 nm track width and 13 nm minimum feature size, fabri-

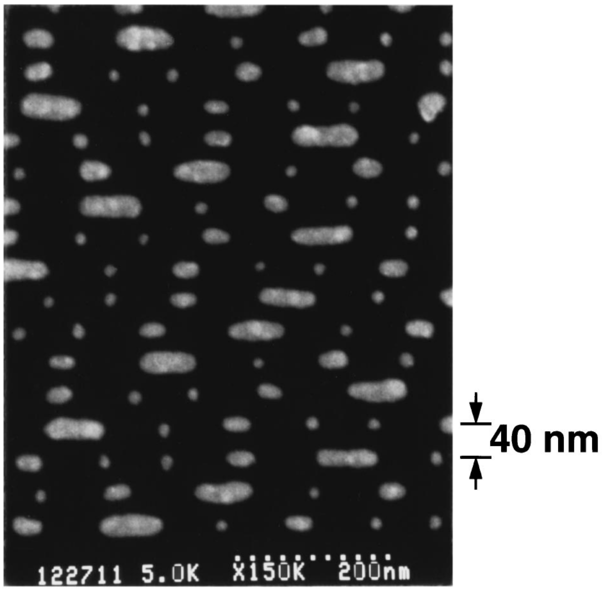


FIG. 3. SEM micrograph of a 40 nm track width Nano-CD fabricated with nanoimprint lithography and liftoff.

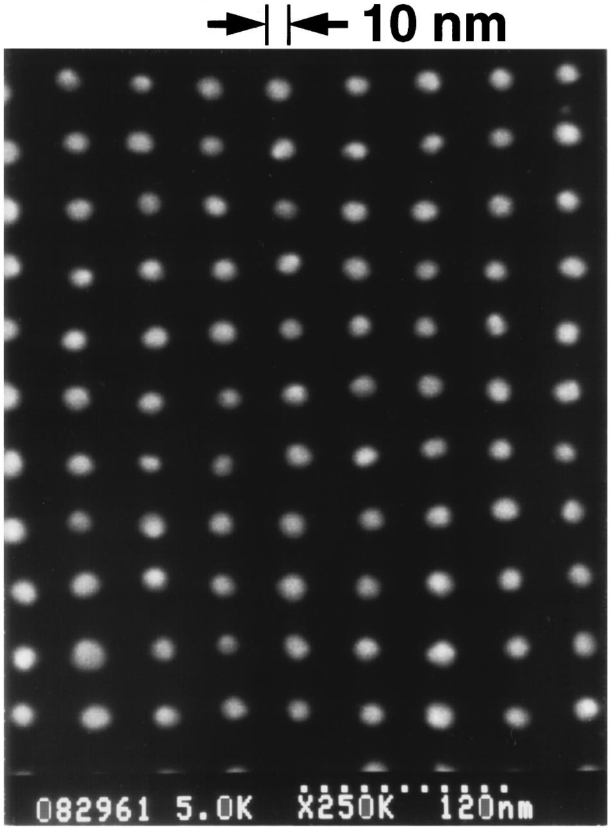
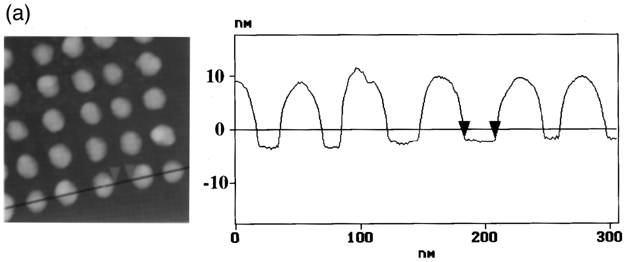
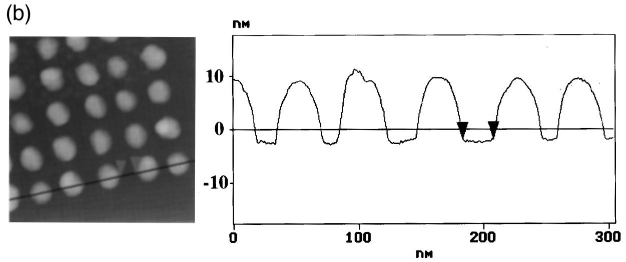


FIG. 4. SEM micrograph of a Nano-CD consisting of 10 nm metal dots with a 40 nm period fabricated using nanoimprint lithography and liftoff.

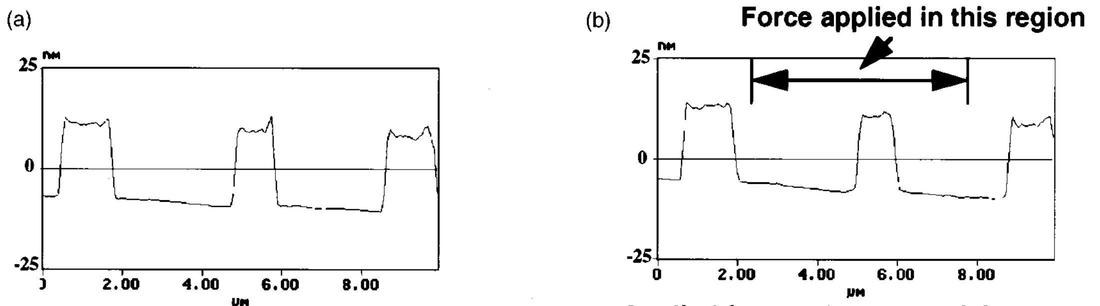


Initial TMAFM image of 50 nm period Nano-CD.



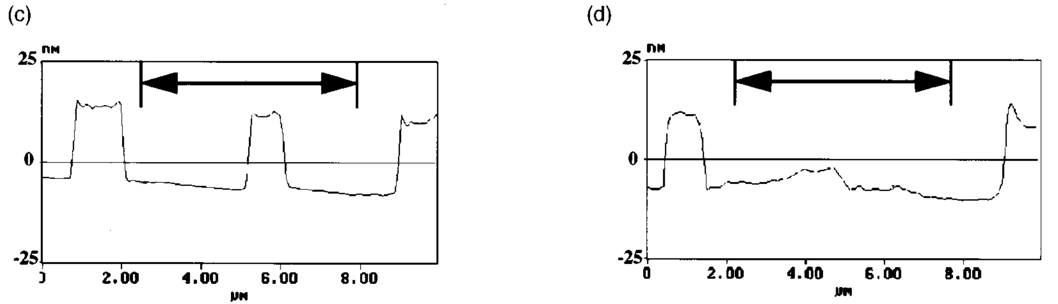
TMAFM image after 1000 scans of Nano-CD.

FIG. 5. Initial tapping mode AFM image (a) and 1000th image (b) of a Nano-CD consisting of 50 nm period gold dots fabricated using nanoimprint lithography and liftoff.



Initial image

Applied force = 11 μN, no visible wear



Applied force = 15 μN, no visible wear

Applied force = 19 μN, structures removed by tip

FIG. 6. Cross sections of contact mode AFM images showing wear of chrome grating after various applied forces using a silicon scanning probe tip. The images are for (a) initial, (b) 11 μN, (c) 15 μN, and (d) 19 μN applied force. Only at the 19 μN force the tip removes the Cr grating.

cated using the mold shown in Fig. 2. This track width corresponds to a storage density of 400 Gbit/in^2. Figure 4 shows another 400 Gbit/in^2 Nano-CD with 10 nm minimum feature size and 40 nm pitch. Gold was chosen due to its high contrast on the silicon substrate in the scanning electron microscopy (SEM). Other materials may also be used which offer better wear properties than gold, as discussed later.

A high-resolution and nondestructive technique is needed to read data stored in the nanoscale topographical bits of a Nano-CD. The bits are too small to be read by current laser beams as used in CDs. Information stored on Nano-CDs was read back using an atomic force microscope (AFM) with commercial silicon scanning probes. Both tapping mode and contact mode AFM were investigated. Figure 5(a) shows a tapping mode AFM image and a cross-section profile of a Nano-CD consisting of a uniform array of gold dots with a 50 nm period. Tapping mode AFM images show the gold dots are wider than the 10 nm measured by SEM. The discrepancy is attributed to the scanning probe's tip size. The cross-section profile indicates that the probe tip can resolve individual nanoscale dots and the flat silicon substrate between the 50 nm period dots. However, for 40 nm period dot arrays with the same diameter, the probe tip could not always reach the substrate, making the dot height measured by AFM smaller than that for 50 nm period dots. This problem can be avoided by using a sharper probe.

The wear of Nano-CDs and the scanning probe during read-back process was investigated. Tapping mode AFM (a force range of 0.1–1.0 nano-Newtons) was used to scan the same location of the Nano-CD 1000 times as shown in Fig. 5(b). We did not observe any discernible change in the AFM image. This indicates that neither the silicon proximal probe nor the Nano-CD exhibited significant wear during the tapping mode AFM imaging.

To accelerate the wear test of the tips and the disks, contact mold AFM and large tip forces were used. Moreover, the gold dots were replaced by a 15-nm-thick chrome grating of a 3 μm spacing and linewidth fabricated using photolithography and liftoff. Chrome has a Mohs hardness of 9, making it more resistant to wear than gold, which has a hardness of 2.5. The magnitude of the applied forces depends upon the spring constant of the proximal probe cantilever. The AFM tips used in the study were 125-μm-long commercial silicon cantilevers which had spring constants ranging from 20 to 100 N/m. Since the spring constant of the cantilevers was not accurately known, the approximate forces were calculated using a spring constant of 60 N/m.

Figure 6 shows 10-μm-wide cross-section profiles from contact mode AFM images of the chrome grating after various forces were applied to the center 5-μm-wide section. We found that the AFM tip force can be increased to 15 μN without creating immediate noticeable change in the AFM image. However, at 19 μN force, the silicon tip will remove the chrome line during scanning. This test indicates that in tapping mode, where the AFM tip force can be over four orders of magnitude smaller than the damage threshold, both the Nano-CD and silicon probe tip should have a lifetime that is at least four orders of magnitude longer than that at the damage threshold (although the exact relation between the wear and the force is unknown). High data retrieval rates may be obtained by using arrays of scanning probe tips operating in parallel.

[1] B. D. Terris, H. J. Mamin, and D. Rugar, 1996 EIPBN, Atlanta, GA, 1996; B. D. Terris, H. J. Mamin, M. E. Best, J. A. Logan, D. Rugar, and S. A. Rishton, Appl. Phys. Lett **69**, 4262 (1996).

[2] S. Y. Chou, P. R. Krauss, and P. J. Renstrom, Appl. Phys. Lett. 67, 3114 (1995); Science **272**, 85 (1996).