



Cover Article

Ultrahigh-density recording: Storing data in nanostructures

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Electronic storage densities are increasing exponentially. Commercial hard disk drives already boast of storage capacities in the vicinity of 300 Mbit/in², while in the laboratory, IBM has recently achieved a density of 3 Gbit/in². It is now apparent that further increases in storage densities are limited primarily by the nature of the recording media. A new paradigm is proposed here for achieving ultrahigh recording densities in which discrete, magnetic elements, embedded in a nonmagnetic disk by an electron beam, replace continuous, thin-film magnetic media [1]. The name given to this new recording medium is the "quantum magnetic disk" (QMD).

One of the striking properties of the discrete, single-domain element is that, in the absence of an applied magnetic field, each element magnetizes itself, and its magnetization has only two possible states: equal but opposite magnetic moments (i.e., north or south). Each of these magnetic elements can store a bit of binary information. Another striking property is that the magnetic field needed for switching the magnetization direction can be controlled through the element's geometry.

Other advantages of the QMD recording concept include a greatly simplified writing process, individual tracking, low noise (crosstalk), high thermal stability, and ultrahigh density. QMD provides the perfect counterpoint to many of the problems associated with conventional magnetic recording. To date, a storage density of 65 Gbit/in²—over two orders of magnitude greater than the density claimed for thin-film media—has been demonstrated with the QMD recording media [2,3]. The fabrication technology used to make the QMD is similar to that used to make integrated circuits. Finally, a low-cost method for mass producing these disks, called "nanoimprinting," has been demonstrated in the laboratory [3,4].

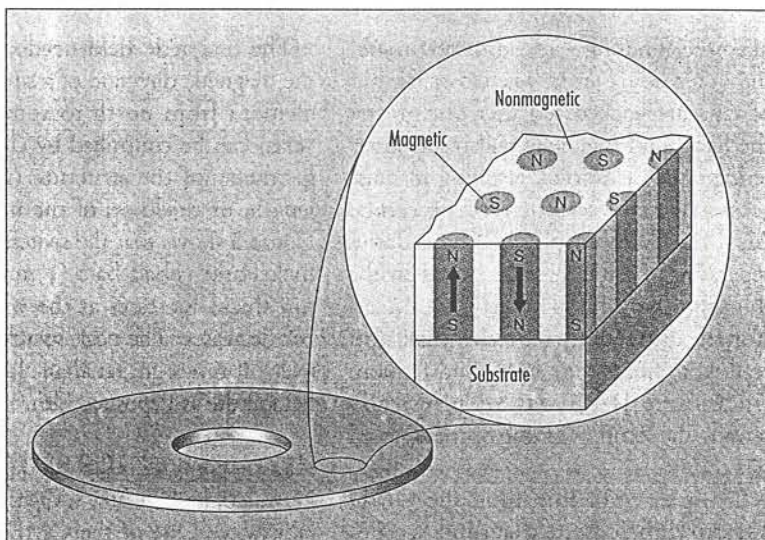


Figure 1. Schematic of a quantum magnetic disk. Prefabricated, discrete, single-domain magnetic elements are embedded in a nonmagnetic material. Only perpendicular magnetization is shown, but the disk can also be made offering longitudinal magnetization.

The advantages that QMD offers can be better appreciated if we first look at some of the hurdles that must be overcome in achieving high storage densities with conventional magnetic disks, where data is stored on a continuous, thin film of magnetic recording media supported by a rigid, nonmagnetic substrate. The thin, magnetic film consists of many, randomly oriented, polycrystalline grains. An applied magnetic field aligns a tiny patch of these grains, allowing data to be stored in the thin film. The magnetic moment, size, and location of this area represent a single bit of binary data.

Because the magnetic moments of the grains are randomly aligned in the thin film, the write heads must be very precise in defining the magnetic moment and location of each bit of data recorded on the thin film. A slight error in writing one bit can

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MEDIA.

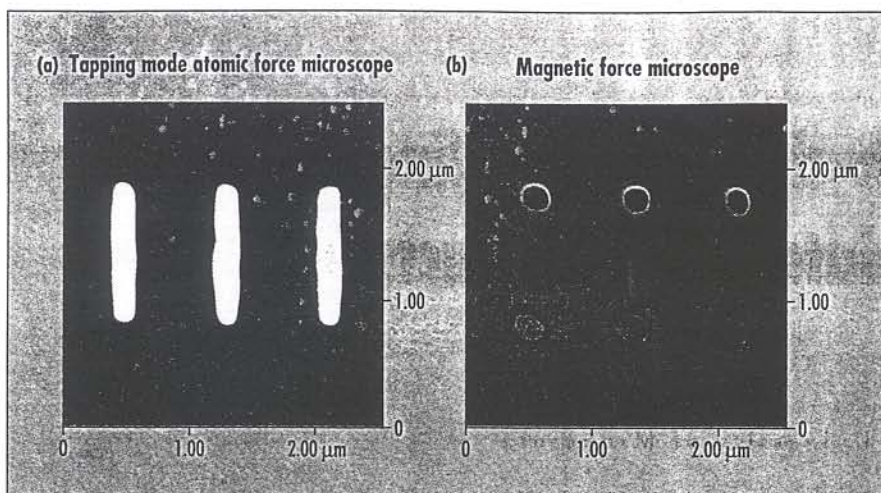


Figure 2. (a) Atomic force microscopy and (b) magnetic force microscopy of single-domain, nickel bars (100 nm wide, 1 mm long, 35 nm thick).

affect neighboring bits, ultimately resulting in a reading error. The closer the bits of data are packed together, the greater the likelihood that they will begin interfering with each other, resulting in noise (crosstalk) and serious reading errors. Also, there are no physical boundaries separating the bits of data stored in the thin film. Each bit is located by calculating the movements of the disk and read/write heads (i.e., in a blind fashion) since there is no way of physically sensing the location of one of these stored bits of data.

In the place of thin film, the QMD uses prefabricated, discrete, single-domain, magnetic elements (e.g., pillars or bars) that have the same shape and are uniformly embedded in a nonmagnetic material (Fig. 1). Each element stores a bit of binary information.

The prefabricated single-domain elements have several unique properties. First, when no external magnetic field is present, the magnetic moment of each discrete is either positive or negative. If the magnetic element is small enough, the magnetostatic energy will fall below the domain wall energy, forming a single domain. The shape anisotropy of the discrete single-domain element forces its magnetization along the element's long axis. In Fig. 2, a magnetic force microscope reveals nickel bars that are 100 nm wide, 35 nm thick, and 1 mm long, and only two magnetic poles at the ends of each nickel bar, with no poles in between—a clear picture of a single-domain, magnetic element.

The magnetic field needed to switch the magnetic direction of a single domain element from north to south (or vice versa) can be controlled by changing the geometry of the structure (i.e., width, length, or thickness of the nickel bars). Figure 3 shows that the switching field of nickel and cobalt bars (1 mm long, 35 nm thick) increases as the width of the bar decreases. The peak switching field is over 30 times greater than the switching field of the as-deposited film.

FABRICATING A QUANTUM MAGNETIC DISK

Now, let's look at how a QMD might be fabricated. One of the QMD structures fabricated in our laboratory consists of single-domain nickel (magnetic) nanopil-

lars uniformly embedded in an SiO_2 (nonmagnetic) disk [3]. Electron-beam lithography was used to define the size and location of each bit in the disk, while reactive ion etching was used to create an SiO_2 template (Fig. 4). Next, nickel was electroplated into the template openings, after which the disk was polished to planarize the surface of the disk.

The properties of the QMD have been investigated using scanning electron microscopy (SEM), tapping mode atomic force microscopy (TMAFM), and magnetic force microscopy (MFM). A SEM micrograph (Figure 5a) shows a top view of a 3-bit \times 3-bit section of the QMD. The micrograph reveals nickel pillars, 50 nm in diameter, with a 100-nm period corresponding to a magnetic storage density of 65 Gbit/in².

TMAFM and MFM images taken simultaneously on the same area of the QMD are shown in Figs. 5b and 5c, respectively. The TMAFM image of a 3-bit \times 3-bit section of the QMD indicates that the topology of the nickel pillars is indistinguishable from that of the SiO_2 . The surface is very smooth with a roughness of 0.5 nm root-mean-squared. The corresponding MFM image, on the other hand, clearly shows that each bit has a quantized magnetization orientation and that the magnetic image of each pillar of the 9-bit section can be resolved. Five bits show a south orientation (red color), while four bits point north (blue color). The QMD was

MASS PRODUCING QUANTUM MAGNETIC DISKS BY NANOIMPRINTING

There is a great need to develop low-cost technologies for mass producing sub-50-nm structures since such technology can have an enormous impact in many areas of engineering and science.

Imprint technology using compression molding of thermoplastic polymers is a low-cost, mass manufacturing technology that has been around for several decades. Features with sizes greater than 1 μm have been routinely imprinted in plastics. Compact disks based on imprinting of polycarbonate is one example. However, no one has ever imprinted sub-25-nm structures

with high aspect ratios into polymers.

In the nanoimprint process, a mold is pressed into a thermoplastic polymer that is heated above its glass transition temperature. Above that temperature, the polymer has a low viscosity and can flow, thereby conforming to the mold. The nanostructures imprinted in the polymers conform completely with the geometry of the mold. The nanoimprint process offers a low-cost method for mass producing sub-25-nm structures. At present, the imprinted size is limited by the size of the mold used. —Peter Krauss

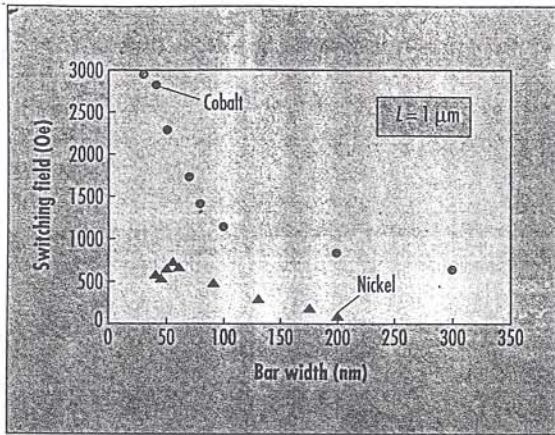


Figure 3. Effect of bar width on switching field of nickel and cobalt bars (35 nm thick, 1 mm long).

demagnetized before imaging, therefore the nearest neighbor bits have opposite magnetic directions. This magnetic configuration represents the lowest energy state for the QMD. The sidewall of the pillars, where SiO₂ was removed, is very smooth (Fig. 6).

PERFECT WRITING, LESS CROSSTALK

The QMD greatly simplifies the writing process. Instead of having to precisely define the magnetic moments, area, and location of each bit, as when writing on a conventional magnetic disk, the writing process in a QMD simply entails changing the magnetic direction of a discrete single-domain bit. Micro-magnetic simulation has shown that even if a writing field is smaller than the size of the bit, it will flip the magnetic direction of the entire bit, leading to error-free writing [5].

Moreover, a minor overlap of the writing field with a nearby bit perturbs its magnetic moment only as long as the field is present. Once the writing field is removed, the bit returns to its original magnetic state. The writing process in QMDs is quantized: a write head either writes the entire bit perfectly, or it does not write the bit at all. The quantized writing process in the QMD will allow the use of a smaller—and therefore faster—write head and will avoid the errors due to the misplacement and the fringing field of the write head. Hence, it is suitable for ultrahigh-density storage.

With a QMD there's less crosstalk between bits. The crosstalk in conventional disks results from intergranular exchanges as well as magnetostatic inter-

actions. By replacing the ferromagnetic material existing between bits in thin-film media with a nonmagnetic material, the exchange interaction in a QMD is cut off completely, while the interbit magnetostatic interaction is greatly reduced.

In conventional magnetic disks, the bits aren't always separated by physical boundaries. To be able to track each bit requires leaving a tracking mark (writing code) during the writing process. The disk

rotates until the data is aligned with the read/write head. Over 14% of total disk space is taken up with these tracking marks in commercial disks. More space will need to be devoted to tracking as the areal density of the disk increases.

Since each implanted bit in a QMD is isolated by nonmagnetic materials, there is always a variation in the magnetic field between bits that provides the signal for tracking each bit. In other words, in a QMD drive, tracking is never "blind"—each bit can be physically detected prior to writing or reading.

A QMD also generates less reading noise. Because of magnetic interactions

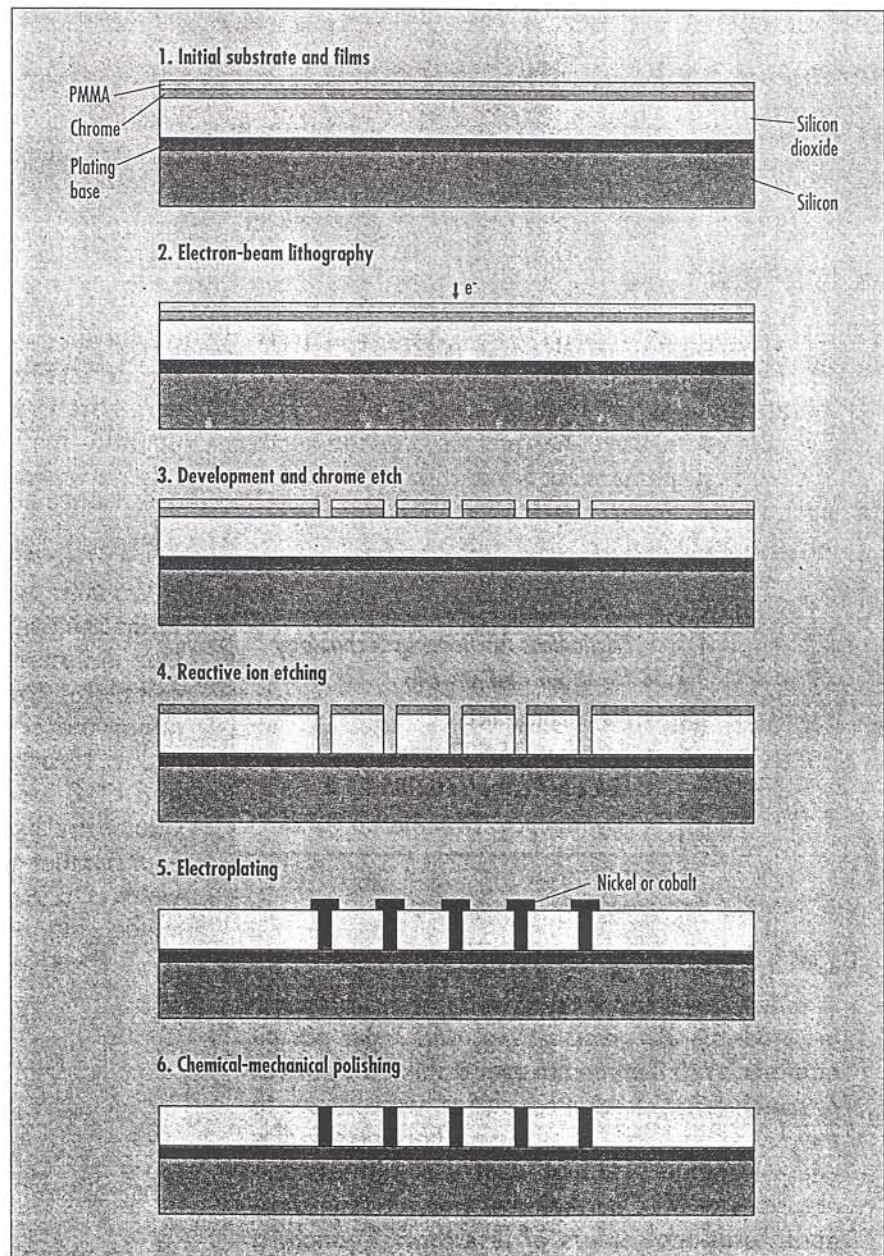


Figure 4. QMD fabrication process using electron-beam lithography, reactive ion etching, and chemical and mechanical polishing.

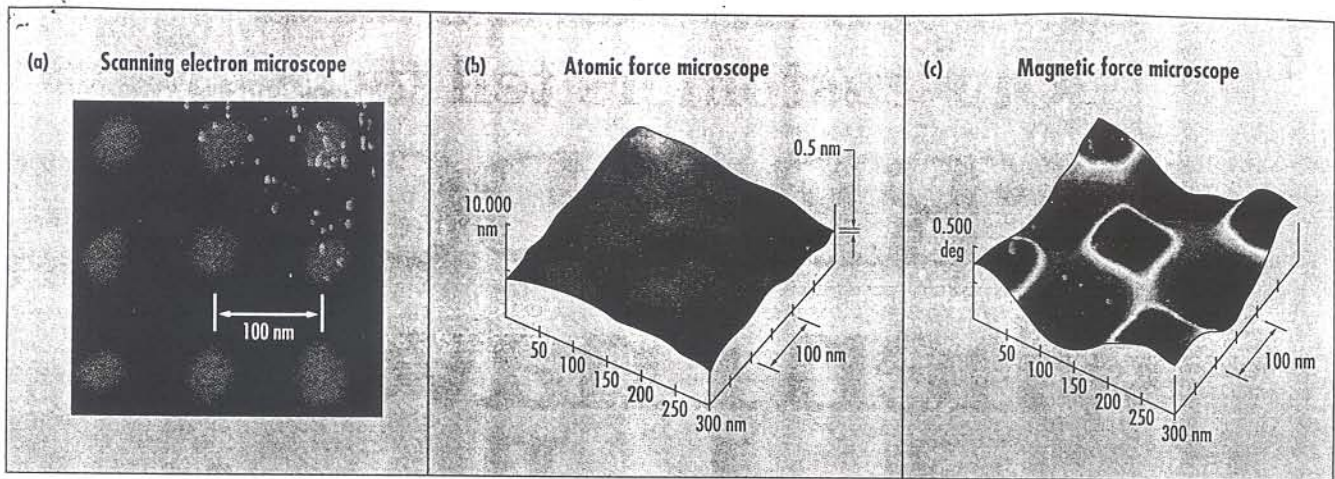


Figure 5. (a) Scanning electron microscope image of a 3-bit \times 3-bit section of QMD (top view) with 65-Gbit/in² density. Each bit consists of a nickel pillar uniformly embedded in 200 nm SiO₂. (b) The tapping mode atomic force microscopy (TMAFM) image shows a very smooth surface, while the (c) magnetic force microscopy (MFM) image shows an alternating pattern of magnetization directions for each bit.

and varying grain sizes, the boundaries between the "0" and "1" bits in a conventional, thin-film disk are ragged, leading to reading noise.

In a QMD, however, the boundaries between the bits have been defined lithographically and are very smooth, producing quiet reading signals.

In conventional thin-film magnetic disks, higher storage densities mean shrinking grain size; the smaller grains are necessary to maintain the grains-per-bit, and hence signal-to-noise, ratio. The grains also have to be more effectively isolated from each other to prevent random collaborative switching caused by intergranular exchange interactions. These interactions grow weaker as grain size shrink, ultimately reaching the superparamagnetic limit where thermal energy alone can trigger random magnetic

switching of the grains, at which point all stored data is effectively lost.

In a QMD, the polycrystalline grains in each discreet bit are strongly coupled. The bit behaves more like a relatively large grain, with a switching energy much greater than the superparamagnetic limit. In other words, the QMD is thermally stable even at high bit densities.

Our research shows that with nanofabrication technology the density of QMDs can reach 0.25 Tbit/in² (Fig. 7). This will require the development of ultrahigh-resolution, high-speed, read/write heads as well as new drive systems. The heads will probably be in the form of large parallel arrays. The disk drive itself may require linear, rather than rotational, motion. A QMD capable of storing 30 Gbit of data may be smaller than a penny. ▲

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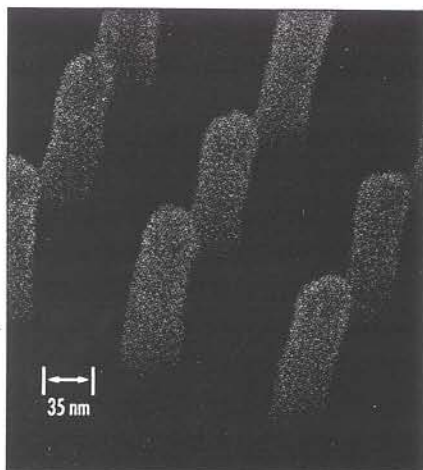


Figure 6. SEM image of 35-nm-diameter nickel pillars spaced 100 nm apart.

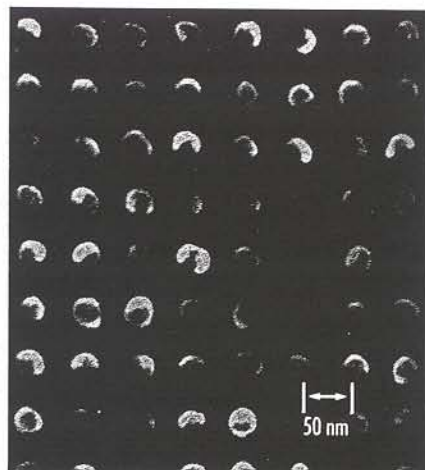


Figure 7. SEM image of metal dot arrays with a density of 0.25 Tbit per in².