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Quantum magnetic disk

Stephen Y. Chou *, Peter R. Krauss

NanoStructure Laboratory, Department of Electrical Engineering, University of Minnesota, Minneapolis, MN 55455, USA

Abstract

A quantum magnetic disk (QMD) – a new paradigm for magnetic recording – is proposed and fabricated. The QMD consists of pre-fabricated single-domain magnetic structures that have an identical shape and are uniformly embedded in a nonmagnetic disk. Each single-domain structure has a quantized magnetic moment and can store one bit of information. The QMD has a number of advantages over the conventional disk and is suitable for ultra-high density recording. Two processes based on electron beam nanolithography and other nanofabrication technologies have been developed to fabricate QMDs. QMDs with a density of 65 Gbits/in^2 – over two orders of magnitude greater than the state-of-the-art magnetic storage density – have been demonstrated. A method for mass production of QMD without employing lithography is discussed.

1. Introduction

In a conventional magnetic disk (CMD), a writing head must simultaneously define the location, shape, and magnetization moment of each bit. A slight error in doing so could lead to errors in reading the bit and neighboring bits. The bits on CMDs are stored in a continuous thin magnetic film. Often, there are no recognizable boundaries between bits, making their reading and writing 'blind' and dependent solely upon the mechanical accuracy of the drive. The continuous film also can exhibit cross-talking in high density storage, namely the switching of one bit will automatically switch a neighboring bit due to the exchange force.

Naturally, one could ask whether it would not be better if the writing head did not need to define the location, shape and magnetization moment of each bit? Wouldn't it be better if the disk drive could see each bit before reading and writing it? Wouldn't it be better if the exchange force between the bits and hence the cross-talk could be reduced? The quantum magnetic disk (QMD) – a new paradigm for ultrahigh density magnetic disk that we proposed here – is a major step in this direction [1].

2. Quantum magnetic disks

A QMD consists of pre-fabricated single-domain magnetic structures (e.g. array of bars or pillars) that have an identical shape and are uniformly embedded in a nonmagnetic disk, as shown in Fig. 1. The magnetic moment of each single-domain structure has only two quantized states: the same in magnitude but opposite in direction. Therefore, each single-domain structure can store one binary bit of information.

QMDs have a number of advantages over CMDs making them suitable for ultra-high density storage as shown in Fig. 2. First, the writing process in QMD is greatly simplified. Unlike CMDs where the writing process must define the location, shape, and magnetization moment of a bit, the writing process in QMD just simply flips the quantized magnetization orientation of a pre-patterned sin-

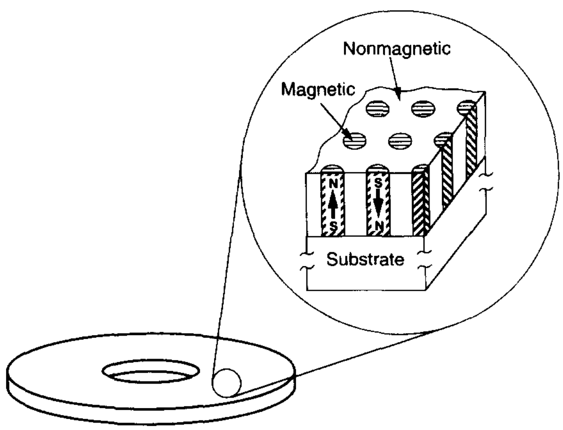

Fig. 1. Schematic of a QMD. Only the vertical magnetization is shown, but the disk can also be made with longitudinal magnetization.

* Corresponding author: Fax: +1-612-625-4583; email: chou@ee.umn.edu.

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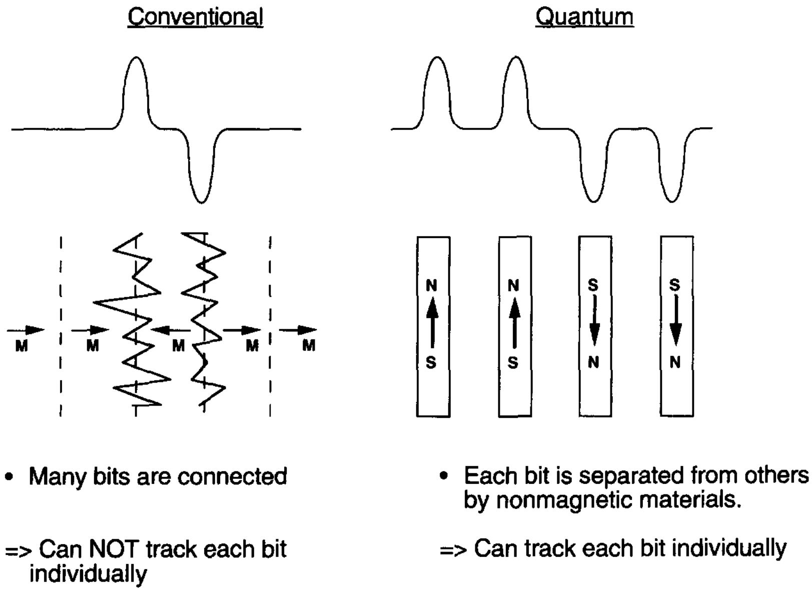

Fig. 2. Comparison of writing, reading, and tracking of bits in CMDs and QMDs.

gle-domain magnetic structure. This means that in a QMD, even when the writing head partially overlaps with neighboring bits, it is still possible to write perfectly just the intended bit without altering the neighboring bits as long as the writing head overlaps with the intended bit most. This also implies that a perfect writing in QMD can be achieved with a writing head of a size that is much smaller or larger than the size of a bit. In other words, in QMD, the precise definition of the bits is done only once during disk fabrication with relatively low cost due to mass production. As a result, the requirements for the writing process which constantly occurs during disk usage can be relaxed.

Second, QMD can track every bit individually but CMD cannot. This is because in a QMD, each bit is separated from the other bits by nonmagnetic material, but in CMD many bits are connected. The individual-bit-tracking ability allows precise positioning and lower error rate.

Third, reading in QMD should have much less jitter than that in CMD. The reason is that in CMDs, the boundary between bits is ragged due to grain size; in QMD, each bit can have edges much smoother than the grain size and is well separated from other bits.

Fourth, the non-magnetic materials which separate the bits in a QMD cut off the exchange interactions between the neighboring bits, thus greatly reducing the crosstalk problem.

And fifth, by controlling the size and shape anisotropy of each bit as well as the interface between the bit and nonmagnetic material, one can achieve unique coercivity and switching processes in the single-domain magnetic structures which may be impossible in thin film storage media.

3. Fabrication

Two fabrication methods have been developed for fabricating QMDs with perpendicular magnetic moment. The first method results in ultrahigh density arrays of free standing nanoscale single-domain nickel structures [2]. The

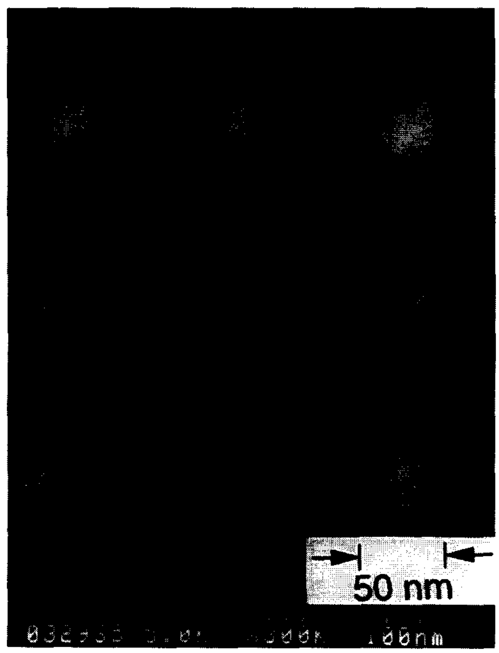

Fig. 3. SEM image of 3 by 3 bits of a QMD with 65 Gbits/in^2 density. Each bit consists of a nickel pillar uniformly embedded in 200 nm SiO_2 with a 50 nm diameter (aspect ratio of 4) and a period of 100 nm.

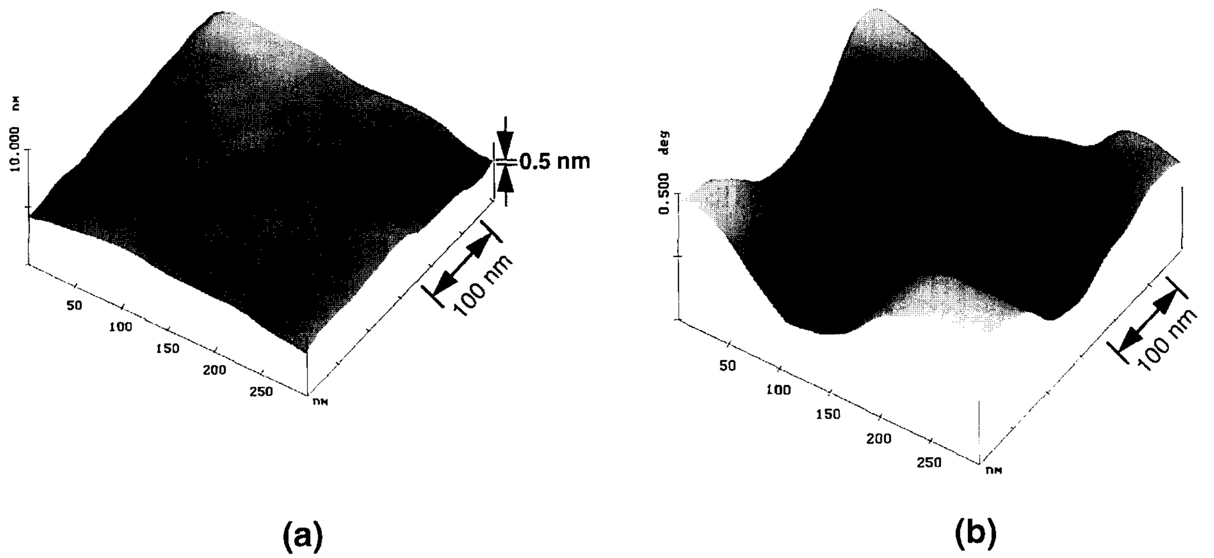

Fig. 4. TMAFM image (a) and MFM image (b) of 3 by 3 bits of a QMD with 65 Gbits/in^2 density. The TMAFM image shows a very smooth surface and the MFM image shows an alternating pattern of bit magnetization directions.

fabrication process begins with a silicon substrate onto which a thin plating base and PMMA film were deposited. First, a high resolution electron beam lithography system was used to expose dot arrays in the PMMA. The exposed PMMA was removed in a development process. Second, an electroplating process was used to selectively deposit nickel into the PMMA template openings. Third, the PMMA was removed leaving free standing nickel pillars.

The second QMD fabrication method results in ultra-high density arrays of nanoscale single-domain nickel structures embedded in a SiO_2 film with an extremely smooth top surface [3]. The fabrication begins by depositing on a silicon substrate a thin plating base, SiO_2 film, chrome film, and PMMA film. First, electron beam lithography was used to expose dot arrays in the PMMA. After developing, the dot arrays were transferred into the chrome film. Second, reactive ion etching was used to etch the array of holes down to the plating base beneath. Third, an electroplating process was used to selectively deposit nickel into the SiO_2 template openings. Fourth, chemical mechanical polishing was used to remove overplated nickel giving a surface with a RMS roughness of 0.5 nm.

4. Characteristics

A QMD of 65 Gbits/in^2 density fabricated using the second process has been investigated using SEM (Fig. 3), tapping mode atomic force microscopy (TMAFM) (Fig. 4a), and magnetic force microscopy (MFM) (Fig. 4b). The TMAFM image shows a very smooth surface with a RMS roughness of 0.5 nm. The MFM image corresponding to the same area clearly shows the 3 by 3 bit array has an alternating magnetization pattern. One orientation of magnetization is indicated by bright spots, and the other orientation by dark spots. For these measurements the QMD was first demagnetized. The magnetization orientation of individual bits can be switched using the localized magnetic field from an MFM tip thereby writing data on the QMD.

5. Fabrication without nanolithography

To mass produce QMD cost-effectively, a process without using lithography must be developed. One of the candidate processes is to make a mold that contains an array of uniform pillars [4]. The mold will create uniform vias in a nonmagnetic layer on top of disks by molding. Then magnetic materials will be deposited in the vias by CVD, electroless plating, or other methods. Finally, chemical mechanical polishing will be used to achieve a smooth finished surface.

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